Determination of the Available Transfer Capability in a Deregulated Power System

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Certificate

It is certified that the work contained in this thesis entitled **DETERMINATION OF THE AVAILABLE TRANSFER CAPABILITY IN A DEREGULATED POWER SYSTEM** by *Anshuman Srivastava* has been carried out under the joint supervision of Prof Dr -Ing Jurgen Stenzel, Technische Universitat Darmstadt, Germany and myself This work has not been submitted elsewhere for a degree

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Evaluation of the Master Thesis

Determination of the Available Transfer Capability in a Deregulated Power System

Under my supervision and the guidance of Dipl.-Ing. Kristján Halldórsson Mr. Srivastava prepared his thesis. After being introduced to the subject he worked independently and he was very diligent. He designed, implemented and tested a theoretical model to calculate available transfer capability For this purpose he considered both static and dynamic criteria of power systems. Considering the various aspects of his thesis (research work, results, written thesis and presentation) my evaluation leads to the mark very good

(German marks. 1 very good, 2 good, 3 satisfactory, 4 sufficient, 5 unsatisfactory)

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Abstract

Power industries in many parts of the world have been deregulated to introduce competition among the market participants and bring several competitive opportunities A fair competition needs open access and non-discriminatory operation of the transmission network. Open access to the transmission system places an emphasis on the intensive use of the interconnected network reliably, which requires knowledge of the network capability. Available Transfer Capability (ATC) is a measure of the remaining power transfer capability of the transmission network for further transactions This work gives an approach to calculate ATC of the transmission path. ATC determination models are developed using the static and dynamic criteria. Under static criteria, line thermal limit, bus voltage limit, generator real and reactive power limit and voltage stability limits are considered. The Newton Raphson load flow method and the continuation power flow method are used as tools for static ATC calculation The static ATC determination model is tested on two real systems, the Icelandic 220kV system and the UPSEB 400kV system of India. Under dynamic criterion, only steady state stability limit has been considered. The dynamic ATC determination model is tested for a single machine infinite bus (SMIB) system. The developed models provide a step-by-step procedure for ATC calculation. It calculates the transfer capability for each of the static and dynamic criteria and indicates the limiting condition that restricts the value of ATC.

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Abbreviations

ATC	:	Available Transfer Capability
CBM	:	Capacity Benefit Margin
FERC		Federal Energy Regulatory Commission
ISO	:	Independent System Operator
LP		Load Parameter
NERC		North American Electric Reliability Council
PROCOSE		Probabilistic Composite System Evaluation Program
SMIB	:	Single Machine Infinite Bus System
TC		Transfer Capability
TC1		Transfer Capability of the transmission path with all elements present in the system
TC11	:	Transfer Capability of the transmission path with all elements present in the system considering thermal limit, bus voltage limit and generator real and reactive power limit
TC12	:	Transfer Capability of the transmission path with all element present in the system considering voltage collapse condition
TC2	:	Transfer Capability of the system considering different contingency conditions
TC21	:	Minimum of the Transfer Capabilities calculated for different contingency condition taking one at a time considering thermal limit, bus voltage limit and generator real and reactive power limit
TC22	:	Minimum of the Transfer Capabilities calculated for different contingency condition taking one at a time considering voltage collapse condition
TRM	:	Transmission Reliability Margin
TTC	:	Total Transfer Capability
UPSEB	:	Uttar Pradesh State Electricity Board

Chapter 1

Introduction

In 1990's the restructuring of the electricity industries gained much attention around the world The main focus was to enhance the power system performance, increase the customer focus and reduce the cost revenue. This gave rise to a deregulated system, in which rules were re-regulated to bring competition among electricity market participants like power producers, power consumers, power brokers, etc.

After adopting deregulated system, the structure of the energy market is changed. The vertically integrated system is parted into production, transmission, distribution and market utilities Power production and distribution are made competitive while transmission is still taken as a regulated, monopoly franchise business. An entity, called Independent System Operator (ISO), is introduced. Its responsibility is to organise the operation of the grid and the transmission network in order to get secure and reliable operation of the system while also considering the economic factors. The ISO should perform its functions independently and indiscriminately and does not participate in the market business transactions.

In order to have open access and competition in a market the foremost thing is to provide transparent knowledge about the generation capacity and the transmission capability of the system to the electricity market participants. In a power market, the ISO can check the capability of the transmission path before the transaction of power through it is allowed and provide the information about the available capability of the transmission paths. There comes the use of calculating Available Transfer Capability (ATC) of the transmission path, which is the maximum amount of power above the present transactions that can be transferred reliably from one point to another over the transmission elements without violating certain static and

dynamic security constraints The ISO calculates the ATC of transmission paths and provides this information to the electricity market The market participants then decides and make contracts for the power transactions and other transmission delivery services.

This work gives an approach for the determination of ATC considering both the static and the dynamic examination criteria The calculation of ATC is done using two models, one for static and the other for dynamic criteria, which are developed in this work. The static ATC determination model is tested on two real power systems, the Iceland 220kV system and the Indian UPSEB 400kV system. Newton-Raphson load flow and Continuation power flow methods are used for examining the static criteria. The dynamic ATC determination model is tested on a single machine infinite bus (SMIB) system. Mathematical analysis, eigen-value analysis and time domain analysis are used for the dynamic criterion examination.

In Chapter 2, the role of ATC in a deregulated electricity market will be discussed further In Chapter 3, principles and definitions of ATC used in literature are given. Also the definition of ATC adopted in this work is presented. In Chapter 4, static and dynamic criterions are listed which are examined for ATC determination In Chapter 5, the methods which are used for the ATC determination models and their mathematical formulation are discussed The step by step procedure for the models developed for the ATC calculation is also presented in this chapter Chapter 6 and 7 present the results obtained from the static ATC determination model tested on the Iceland 220kV system and the Indian UPSEB 400kV system, respectively. Chapter 8 gives the results obtained from the dynamic ATC determination model tested on SMIB system The conclusions of the work are finally presented in chapter 9.

Chapter 2

The Role of ATC in a Deregulated Power Market

Before starting with the determination of ATC, it is better to have some brief idea of a deregulated energy market and the importance of calculating ATC in it. Some important aspects of a deregulated market and its general configuration are discussed in this chapter. The functions of ISO (which is assumed to be present in a deregulated power system) are also presented. Then the importance of ATC determination and its uses in a deregulated energy market are described.

2.1 A deregulated power market

The three major elements which has given the way to the implementation of electric industry deregulation are :

- The opening of energy markets
- The unbundling of electricity services
- The open access to the electrical networks

Deregulation is a re-structuring of the rules and economic incentives that governing authority set up to control and drive the electric power industries so that power production and distribution are competitive while transmission is still regulated [1]. Many electric industries are going for the deregulation in order to bring competitive opportunities in the electric market. The purpose of deregulation is to bring privatisation, enhance economic aspects, provide incentives for innovation and increase competition and customer focus in electric industries.

Deregulation provides an open access to all market participants in electric industries. An open competitive market requires that the access to the transmission system by power producers and consumers are managed in a non-discriminatory manner. This may lead to the problem of heavier line loading, increased loop flows, wider variability of transmission pricing as a result of increased use of constrained interfaces, etc if the power transactions are not managed properly. Thus there is a need for detailed transmission planning and operating studies. One mechanism that is considered for ensuring that the access to transmission system is open, non-discriminatory and comparable without effecting the system security and reliability is the formation of an entity called Independent System Operator (ISO) [2].

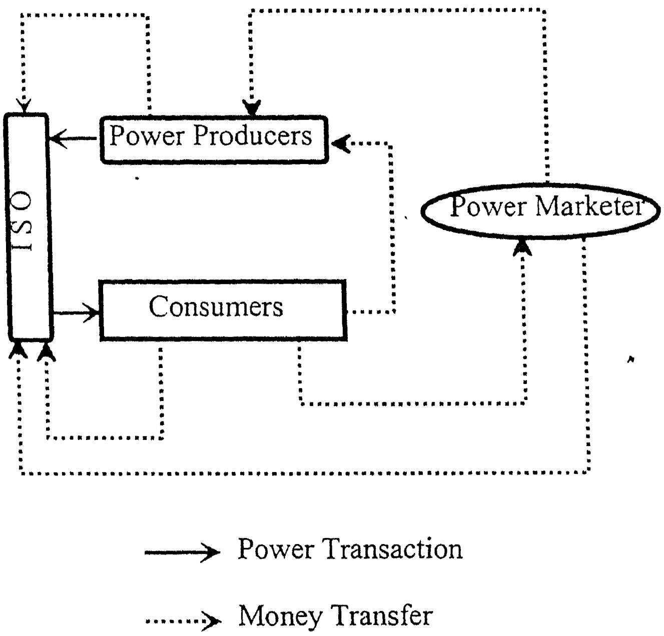


Figure 2.1 : Deregulated energy market configuration

A general configuration of a deregulated market (Figure 2.1) consists of a system operator (ISO), the power producers, the power marketers and the consumers The ISO is an independent authority which does not participate in the market but is only concerned with the power transactions to check the secure and efficient operation of the system. Where as the power producers, the power marketers and the consumers are the market participants which make contracts for power and money transactions in between themselves. Power producers are the conventional and non-conventional generating units in the system. The power marketers act as power dealer in the market which makes power contracts between consumers and power producers according to their needs in order to have some profit. The consumers

have also the privilege to make power transaction contracts directly with power producers. The power transactions taking place between these market participants are checked through the ISO, which decides the validity of the transactions. Before any contract to be held, it should be fit to the ISO criteria. The ISO decision should be abided by all market participants.

The role of the ISO is to provide following services:

1. Planning services
2. Power market administration services
3. Operation planning services
4. Real time operation services
5. Metering, settlement and billing services
6. Open information communication services

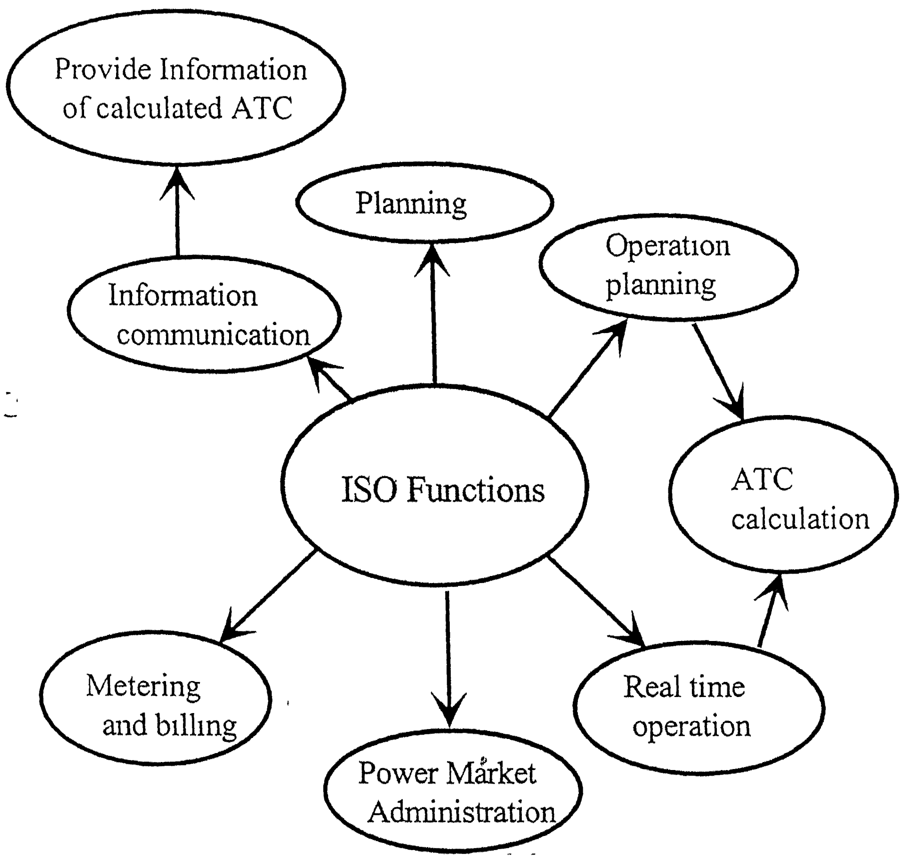


Figure 2.2 : Functions of ISO in deregulated energy market

These services indicate that the ISO is responsible for secure and efficient operation of the power system. The functions of the ISO as defined above are shown in Figure 2 2. It also

indicates the position of ATC calculation as a part of the functions of the ISO. For operation planning and real time operation of the power system, the ISO calculates the ATC to measure the capability of the system. It also displays the calculated ATC value to the market participants through its information channel to provide them a transparent knowledge of the system condition

2.2 Role and importance of ATC

In a new competitive environment, the consumers normally want to access the least expensive power sources available. The suppliers want to access the most profitable markets. This can affect system security and reliability limits. Thus to be able to transfer electric energy reliably from supplier to consumer in the most economical manner it is important to provide some useful information about the system performance to the electric market. The commercial success of the electric market depends on these accurate and up to date information [3]. This poses new challenges to the ISO. Under the responsibility of operation planning and real time operation of the system, the ISO has to analyse the present status of the system and also compute the future possibility of power transactions between the power suppliers and the consumers while maintaining the system security and reliability criteria

One of the key indicator of the network performance is the power which is available for the further transactions through transmission elements above its present transfer without violating the reliability and security criteria, known as Available Transfer Capability (ATC) of the system Operating a power system within its ATC limits ensures that the system will continue to supply electric power on demand, even under certain abnormal conditions. This ATC information can be used for the commercial marketing of electricity, that is the ATC information is useful for deciding the new power transaction reservations between the market participants. The ATC is calculated and provided by the ISO to indicate the system capability for further power transactions. Then the customer decides and reserves the transmission delivery services like amount of power to be transacted, the transmission path, the time period of reservation and ancillary services required or as defined by the ISO.

The information of ATC, as an important indicator of the system performance, is useful in a deregulated energy market in the following ways :

- It provides the knowledge of power system capability above the present system condition
- Running the system under the ATC limits also ensures system security and reliability to some extent, since the calculation of ATC is based on the security constraints with the consideration of critical contingencies that can lead the system normal state to alert state [4]
- The ATC is required in making decisions for the transactions between the market participants The market participants check for the ATC of their desired path from the ISO information channel and decide for the power contracts between themselves.
- The ATC is also useful in enhancing system capability. With the knowledge of the limiting condition for the ATC, the system operator can take some operating or planning decision to avoid this limiting condition and thus enhance the system capability. The operating decision may be regarding the scheduling of transmission facilities control setting, for example FACTS devices [5] The planning decision may be enhancement of the power network
- The ATC value can also serve as an indicator of power congestion through transmission lines. With the knowledge of this, system operator can go for the priced-based or other means for congestion relief [6].
- The ATC is useful in transmission costing function. The ISO can put more transmission cost for the transaction through transmission path having low value of ATC. Transmission cost can be allocated in proportion to the ratio of the power transfer and the ATC of the transmission path [7]. This extra transmission cost can be used in increasing the transmission capability for the transmission path.

Chapter 3

ATC Principles and Definitions

A brief idea about the role and the importance of ATC in a deregulated energy market was given in the last chapter. ATC principles which govern the development of ATC definition are presented in this chapter Different definitions which have been used in the literature are discussed These definitions are compared and a concluding definition which is used for the determination of ATC in this work is described.

3.1 Principles for ATC determination

Individual systems, power pools, sub-regions and regions can develop their definitions and methods for calculating ATC which consists of their own reliability planning and operating policies, criteria and guides as required, but it should follow some principles to have non-discriminatory operations between all the areas. An ATC definition and determination method should satisfy certain principles balancing the technical and physical considerations of interconnected network operations with the requirements of open access transmission for competitive electric markets. The following ATC principles [8] govern the development of the definition and the determination method of ATC

1. The ATC value produced by the calculations must give a reasonable and dependable indication of transfer capabilities available to the electric power market.

2. ATC calculations must recognise time-variant power flow conditions on the entire interconnected transmission network. In addition, the effects of simultaneous transfers

and parallel path flows throughout the network must be addressed from a reliability viewpoint

3 ATC calculations must recognise the dependency of ATC on the points of electric power injection, the directions of transfers across the interconnected transmission network, and the points of power extraction.

4 Regional or wide-area co-ordination is necessary to develop and post information that reasonably reflects the ATC of the interconnected transmission network

5 ATC calculations must conform to regional, sub-regional, power pool, and individual system reliability planning and operating policies, criteria, or guides.

6 The determination of ATC must accommodate reasonable uncertainties in system conditions and provide operating flexibility to ensure the secure operation of the interconnected network.

3.2 ATC definitions

By the above principles, a brief idea for available transfer capability could be given as an indicator of additional power in the interconnected electric system which can be moved reliably from one point to another through the transmission elements between those points in the network under specified conditions. The points are defined as source and sink of the electric power. It is time specific and depends upon the parameters and state of the system ATC could be defined by individual systems, power pools, sub-regions and regions according to their operating and planning policies Some definitions used for ATC in different literatures are discussed as follows.

3.2.1 Definition 1

The ATC for a given transmission line at a given time could be interpreted as the difference between the power limitation and the existing power flow [9].

This definition is concerned with the isolated and radial system The transfer capabilities in such a system are mainly based on combination of thermal ratings and voltage drop

limitations But in an interconnected system, due to looped networks some more technical issues come into picture. The system stability can also become an important constraint for some of the area of the interconnected network. Thus ATC calculation requires consideration of some stability criteria too. For a deregulated electric market a wider definition is needed.

3.1.1 Definition 2

*The **ATC** is the limiting transfer value between two control areas (source and sink) that is available without any violation of power system operating properties, e.g thermal overload and voltage limits* [10]

This definition takes into account the power transfer between two control areas in an interconnected network One of the area acts as a source of power and the other as a sink. Thus the direction of power flow is specified. This definition clarifies that the ATC is direction specific The ATC value will change when the source and sink areas are interchanged Thermal overloading of power elements and bus voltage limits are taken as ATC determination criteria. But to have much reliable value of ATC, it is required to consider some more criteria like voltage collapse condition and dynamic stability criteria.

3.1.2 Definition 3

*The **ATC** between two areas provides an indication of the amount of additional electric power that can be transferred from one area to another for a specific time frame and for a specific set of conditions* [8].

The ATC can be a very dynamic quantity because of its dependency on system parameters. These parameters depend upon system conditions which are changing with time. Thus the ATC value is needed to be updated periodically. This definition implies towards the dependency of ATC value on specific time frame and set of system condition.

3.1.3 Definition 4

*The **ATC** indicates how much inter area power transfers can be increased without compromising system security* [11].

Mathematically it can be represented as,

$$\text{ATC} = \text{TTC} - \text{Base Case Transfer} - \text{Some Margin of Safety} \qquad (3.1)$$

According to this definition ATC calculation is based on the system security criteria This security criteria also considers voltage collapse limits. The base case transfer is the initial system condition above which transfer capability is to be calculated. Starting from the base case transfer, total transfer capability (TTC) is determined at which the first security limit is violated Then ATC is determined by Equation 3.1. This definition also introduces some margin of safety which allows some flexibility in system operation This margin of safety takes into account some uncertainties like load forecast error, uncertainty in system topology or variation in facility loading due to the balancing of load and generation within a control area.

3.2.5 Definition 5

The ATC is a measure of the transfer capability remaining in the physical transmission network for further commercial activity over and above already committed uses [8].

Mathematically it is defined as :

$$ATC = TTC - TRM - \text{existing transmission commitments (including CBM)} \qquad (3.2)$$

Where,

- ***Total Transfer Capability (TTC)*** *is defined as the amount of electric power that can be transferred over the interconnected transmission network or particular path or interface in a reliable manner while meeting all of a specific set of defined pre- and post-contingency system conditions.*

- ***Transmission Reliability Margin (TRM)*** *is defined as that amount of transmission transfer capability necessary to ensure that the interconnected transmission network is secure under a reasonable range of uncertainties in system conditions.*

- ***Capacity Benefit Margin (CBM)*** *is defined as that amount of transmission transfer capability reserved for load serving entities on the host transmission system to ensure access to generation from interconnected systems to meet generation reliability requirements.*

- ***Existing transactions*** *is the power flow over the transmission paths at the desired time at which ATC should be calculated* This is the already committed used power on the transmission path

This definition is given by NERC to provide a uniform definition for the ATC determination that satisfy both FERC and electric industries needs It has introduced some new terms like TRM and CBM. TTC calculation is based on the physical and electrical characteristics of the system as applicable under NERC, regional, sub-regional, power pool and individual system reliability planning and operating policies, criteria or guides. The system contingency considered for TTC determination could be single or multiple as defined by the individual electric utility TRM accounts for the inherent uncertainties in system conditions and its associated effects on TTC and ATC calculations. CBM is a part of TTC reserved by the load serving entities in order to meet generation reliability in case of generation deficiency condition

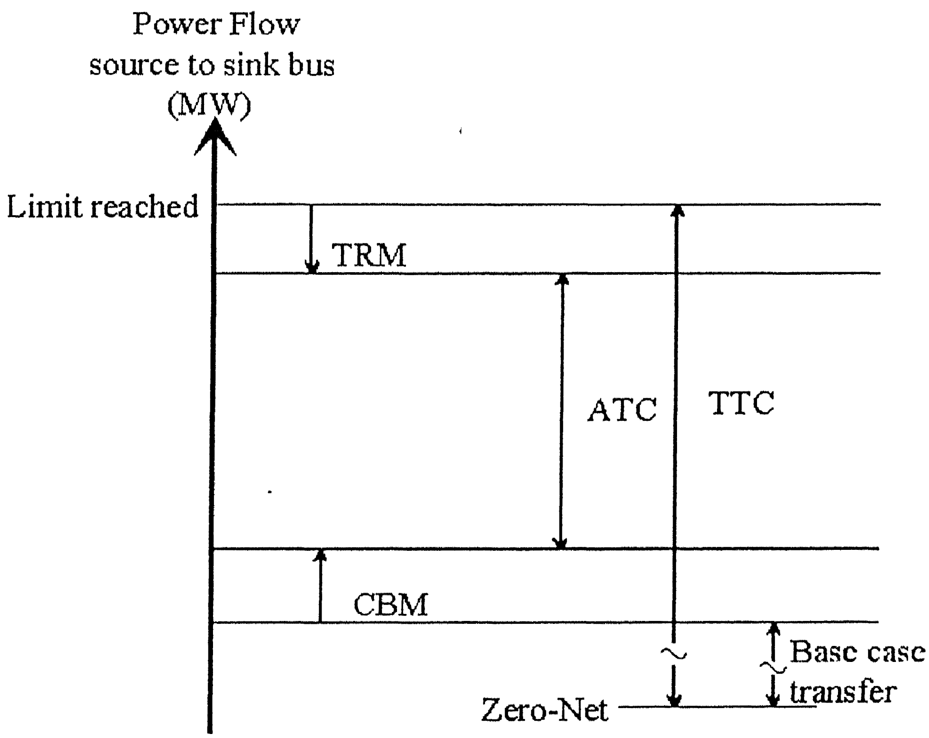


Figure 3.1 ATC and related terms

Figure 3.1 illustrates the relationship between the ATC and the related terms. A base case transfer is the existing power transaction condition on the selected transmission path above which the ATC is to be calculated TTC is the power transfer from source to sink bus at which

the limiting condition is reached TRM and CBM are determined according to the policies of the individual electric system. Then the ATC is calculated using Equation 3.2.

To provide further clarification of the definitions discussed above, they are also compared on the basis of different criteria using the results of calculated transfer capabilities values for the Icelandic 220kV system in Chapter 6.

3.2 ATC definition adopted in this work

All the above definitions indicate towards the limiting maximum power that can be transferred over the desired path This limiting transfer is calculated with respect to some constraints based on the system operating policies. Definitions 4 and 5 also include the calculation of some margin of safety.

Primarily definition (5) could be considered as a general definition. This indicates that ATC calculated should be deterministic and reliable and has a commercial viable value. It considers important factors which are responsible for the reliability and security of the system. It also introduces the terms like TRM and CBM. TRM accommodate uncertainties in the system condition These uncertainties are mainly due to load forecast error or some abnormal conditions arising in the system. In this work the present operating condition data of the system is taken for ATC calculation. No forecast data is used The uncertainties due to abnormal condition are considered by using different contingency criteria for calculating ATC. Thus the calculation of TRM is not required. On the other hand the calculation of CBM requires the knowledge of generation reserves and ancillary services and also some commercial components as recallable and non-recallable power [8]. These are very specific with the policies of an individual system. Since this work mainly concentrate on the criteria and the tools to be used for calculating ATC, therefore the calculation of these margins are neglected in this work. Thus definition adopted in this work is taken as a moulded form of definition (5) in which margin calculation is neglected. The definition is given as :

*The **Available transfer capability** of the transmission path is the amount of power that can be transferred through it, above to its present transfers (base case transfer condition), without violating specific static and dynamic system performance limits to hold reliable, and secure operation. The transmission path is defined by the pair of source and sink buses.*

Determination of ATC depends upon the calculation of Total transfer capability (TTC). TTC is defined as the maximum power that can be transferred through the transmission path without violating specific static and dynamic system constraints.

Thus mathematically TTC and ATC can be represented as :

TTC = Minimum { transfer capabilities (TC's) calculated considering different static and dynamic system constraints } (3.3)

ATC = TTC – base case transfer (3.4)

Where, base case transfer is the power transaction condition above which ATC is to be calculated.

Figure 3.2 clarifies the definition. The TTC is calculated as the minimum of the transfer capabilities (TC's) calculated for different static and dynamic criteria considered for the ATC determination The ATC is calculated as the difference between the TTC and the base case power transfer for the selected transmission path

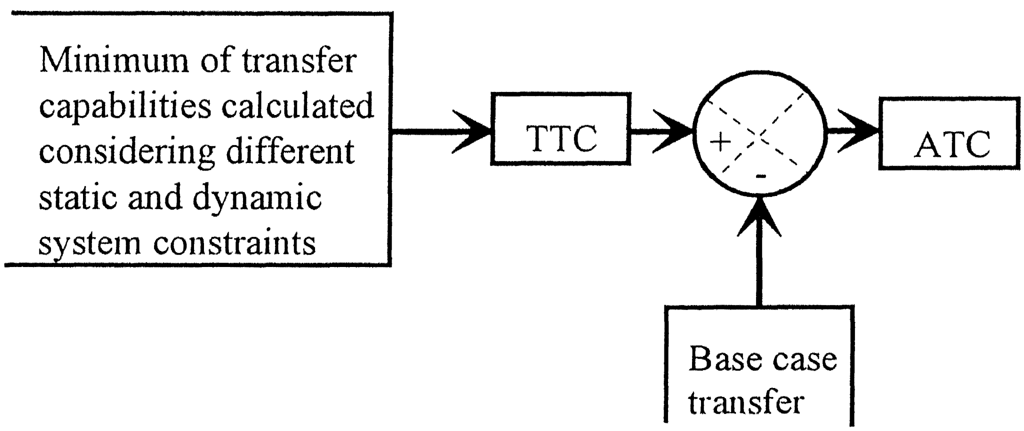


Figure 3.2 · ATC determination

The definition adopted in this work follows the principles discussed in section 3 1 to some extent. The ATC value obtained using this definition provides a reasonable indication of transfer capability available for a specific transmission path. The time variant power flow conditions are considered for ATC calculation by the ATC determination methodology based on this definition The ATC is calculated for a particular “snapshot” of the system conditions As the system conditions change, the ATC has to be recalculated. The definition also considers the ATC dependency on a power injection and consumption points and the direction of the flow of power, since the transmission path is defined by the pair of source and sink buses The static and dynamic constraints specified serve as criteria for the ATC determination. This definition of ATC is used in this work for the development of the model for the determination of ATC

Chapter 4

ATC Criteria

In the previous chapter the definition adopted for this work was discussed This definition serves as a basis for the development of the ATC determination model A literature survey for the ATC determination is presented in this chapter which pave the way for the selecting criteria and tools for the ATC determination model. The static and dynamic stability constraints, which can be used as the criteria for calculating ATC, are discussed.

4.1 Methods for ATC determination : A literature survey

The electric industry is undergoing a fundamental restructuring that brings the competitive opportunity in the power market This results into a variety of energy market structure Ref [12] reviews the present state of restructuring around the world. To enhance the competition in this restructured energy market, it is required to have an open access and non-discriminatory operation. To avoid the undesirable impacts of open access in an energy market such as heavier line loadings and increased loop flows, a clear indication of system ATC is required [3]. A framework for determining ATC of the interconnected transmission networks is given in [8]. The concept for dealing the technical challenges of ATC computation in a deregulated market is presented in [9]. Some theoretical aspects of ATC and the problem associated with its evaluation under open access are discussed in [13]. In [14], the system evaluation tool PROCOSE is used to compute ATC considering the line limits. Ref. [10] describes a method based on the source sink composition for computing the ATC for the selected path. It has developed an ATC calculator in which ATC is calculated by repetitive power flow solution. It considers line thermal limits and voltage limits as ATC criteria. Ref [15] also takes line thermal limits and bus voltage limits as ATC determination criteria

Newton and decoupled power flow methods have been used for ATC estimation Ref. [11] has focused towards the voltage magnitude and voltage collapse limits for ATC calculation. It uses a non-linear power system model and continuation computation method for ATC determination Ref [16] uses a full AC power flow method and the continuation power flow method for ATC calculation considering line thermal loading, voltage limit and voltage collapse limit Ref. [17] defines the role of dynamic constraints in the calculation of ATC and suggests for the calculation of dynamic ATC.

Survey of the above papers indicates different criteria for ATC calculation. Some papers have given emphasis on the voltage collapse criterion for the evaluation of ATC An AC power flow method can be used to consider thermal loading limits, voltage limits and reactive power limits as suggested in [16] Continuation power flow method can be considered as a better tool for the analysis of voltage collapse condition of the system [11]. The new approach in ATC determination is to introduce dynamic criteria in the determination of transfer capability of the interconnected system [17]

This work has considered both the static and the dynamic criteria for the evaluation of ATC in the electric system. The Newton Raphson power flow method and the continuation power flow methods are used for the determination of ATC considering different static constraints such as thermal limits, bus voltage magnitude limits and generator reactive power limits. The steady state stability limit is used as a dynamic constraint for the ATC calculation Load angle calculation, eigen value analysis and time domain analysis are used for the ATC calculation considering dynamic constraint.

Development of ATC determination model requires a discussion on these criteria and the respective methods of analysis. Different static and dynamic criteria used in this work for ATC determination are discussed in the next section while methods and mathematical formulation for ATC determination will be described in the next chapter.

4.1 Static and dynamic criteria

ATC criteria include some performance constraints which should be taken into account for the ATC determination Performance constraints are limitations on power system elements that may be reached during the abnormal or contingency system operations These constraints are

due to physical and electrical characteristics of the system These constraints include the stability criteria of a power system

There are two forms of instability in a power system, the stalling of asynchronous loads and the loss of synchronism between synchronous machines [18] The stalling of asynchronous loads like heaters, lamp and induction motors depends upon two criteria, first the range of the voltage that is available from the source which may be tolerated by the load and second the current carrying capability of the various components in the network. These are considered under static criteria Another form of instability concerns to the loss of synchronism between synchronous machines due to the change in loads or network condition. This is again divided into two types : steady state stability and transient stability These can be considered under dynamic criteria for the ATC determination. Dynamic criteria takes system dynamics into account where as static criteria do not. These static and dynamic criteria should be checked for ATC calculation

4.2.1 Static criteria

Static criteria are concerned with the steady state condition of the power system. These steady state conditions are the pre- and post- contingency conditions when there are no transients remaining in the system. These static criteria correspond to the static security criteria The static criteria considered for the ATC determination are described below

4.2.1.1 Overload limit (Thermal Limit)

Thermal limits are given as the maximum amount of electrical current that can flow through a transmission line or electrical element for a specified time period before these elements are subjected to permanent damage by overheating or result in large sag and thus violating public safety requirements.

Mathematically, it can be presented as :

$$\left| P_T \right| \leq P_{T\max} \qquad (4\ 1)$$

where, P_T is the transmitted power through the electrical element.

Overloading of line can cause a gradual loss of mechanical strength of line and increased sag and decreased clearance to ground due to conductor expansion.

4.2.1.2 Bus voltage limits

The bus voltages should be maintained within the range of acceptable minimum and maximum limits Low voltages can cause inefficient operation of loads like dim light output from lamps, drawing large current by the induction motor for the same torque or in extreme conditions results in motor stalling under load [18] These voltage limits are the operating voltage range, around the nominal voltage at the system buses, that is acceptable by the power system operation and planning authorities. Mathematically it can be represented as :

$$V_{b\,\min} \leq V_b \leq V_{b\,\max} \tag{4 2}$$

where, V_b is the bus voltage.

4.2.1.3 Voltage collapse limit

Voltage collapse is related to the voltage instability of the power system. Voltage instability means progressive or uncontrollable drop in voltage Voltage collapse is an event that occurs when an electric system does not have adequate reactive support to maintain the voltage stability [19] The voltage instability can be better described through Figure 4 1

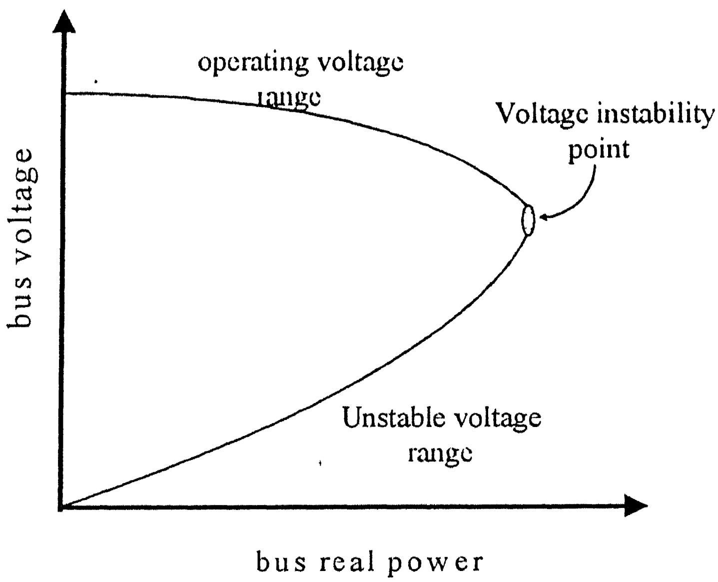


Figure 4.1 : P-V curve

Figure 4.1 shows a typical graph between the voltage magnitude and the real power consumption at a load bus. As the load consumption increases the bus voltage start decreasing with a slow rate But when the power consumption is increased up to a certain critical amount, there is a drastic change in the system behaviour. This critical point is called the voltage

collapse point (saddle node bifurcation point, voltage instability point). At this, the rate of change of voltage with respect to power becomes very large and further increase in power can cause the voltage to dip suddenly resulting in zero bus power i.e black-out condition. Thus voltage collapse may result in interruption of power delivery to customers.

The upper part of the P-V curve represent the stable operating voltage range where as lower part represent the unstable voltage range The power system is operated in order to maintain bus voltages within the upper part of the P-V curve to have satisfactory operating condition.
It is possible in a system to encounter voltage collapse at a voltage level well within acceptable limits [3] Thus, it is also important to check voltage collapse condition besides voltage magnitude consideration

4.2.1.4 Generator Power Limits

The real and reactive power output of a generator are limited. This limitation is determined by the generator capability curve (Figure 4.2). The factors affecting the capability of the generator are given as :

1 Field limit
2. Armature current limit
3 Turbine limit
4. Stability limit (or End ring heating limit)

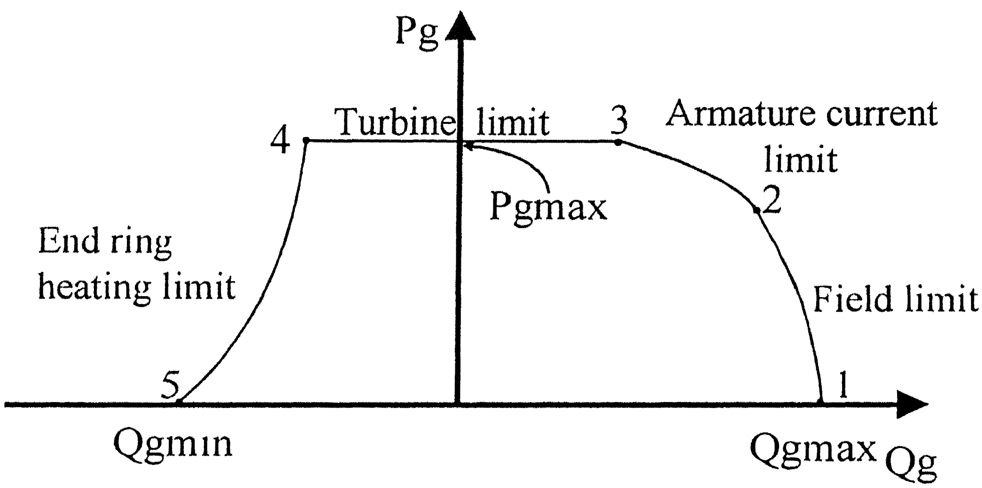


Figure 4.2 · Generator capability curve

Real power generation (P_g) is limited due to turbine limits, where as other factors decides generator reactive power generation (Q_g) limits.

However to simplify the analysis, the limits can be represented as .

$$P_g \leq P_{g\ max} \tag{4 3}$$

$$Q_{g\ min} \leq Q_g \leq Q_{g\ max} \tag{4 4}$$

4.2.1.5 Contingency

Contingency is the unexpected failure or outage of a system component, such as a generator, a transmission line, or other electrical element. A contingency may also include multiple components, which are related by situations leading to simultaneous component outages. In this work, one component contingency (n-1 contingency) has been taken for the ATC determination i e one element outage at a time Static criteria mentioned above are examined under the contingency conditions considered for the ATC determination.

4.2.2 Dynamic criteria

In many cases, point-to-point transfer is not restricted by the static limits, but by the unacceptable dynamic behaviour following a system disturbances. The post-disturbance operating point can be stable, which can be checked through static analysis. But it is also important to ensure that the transition made by the system from the pre- to the post-disturbance operating point is stable. Thus determination of ATC also requires to take dynamic criteria into consideration [17].

Dynamic criteria are checked for the system stability during the transient time from one equilibrium point to another when subjected to some disturbance System dynamics comes into the picture. The stabilities considering the power system dynamics are discussed in the following section.

4.2.2.1 Steady state stability

A power system is stable in the sense of steady state stability at an operating point if on being subjected to a small disturbance it eventually settles to a new or original operating point after the disturbance has disappeared. When the system condition changes the new operating point is described by the new equilibrium state between the system components. The small disturbances can be a gradual or relative slow change in load or generation. The rate of change in load is quite slow as compared with the natural frequency of the power system. The system

considered in this work for the steady state stability study is a single machine infinite bus system This simple system is helpful in understanding the basic effects and concepts involved in the methodology used in this work. This system consist of a generator which is connected to an infinite busbar through a lossless transmission line (Figure 4 3).

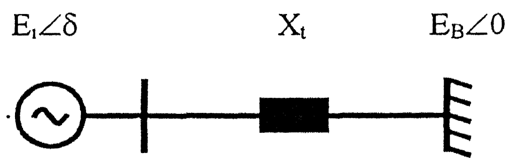


Figure 4.3 · Single machine infinite bus system

The transmitted power from the generator to the infinite bus is given as .

$$P = \frac{E_1 E_B}{X_t} \sin \delta \qquad (4.5)$$

For a constant voltage magnitude and transmission line reactance the power transfer P depends upon the angle δ, which is the difference between the internal angle of the generator and the angle of the synchronously rotating reference axis which in this case corresponds to the infinite bus This angle is known as load angle δ The curve drawn between P and δ is known as power angle curve (Figure 4.4).

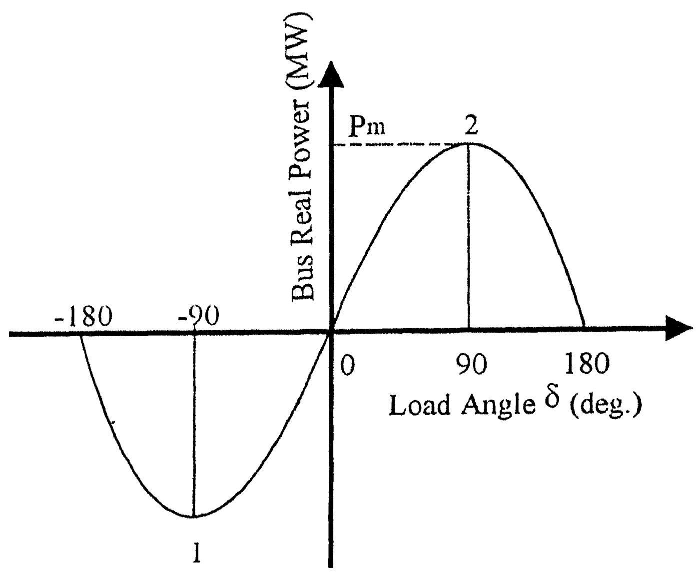


Figure 4.4 : Power-angle curve

At $\delta = 90°$ the maximum power transfer is given as .

$$P = \frac{E_I E_B}{X_t} \tag{4.6}$$

Steady state stability can be clearly described by the power angle curve. When the load connected to the generator is increased, extra power is delivered by the generator with the increase in load angle. The load angle increases to a new value at which the load demand and the power output of the generator are balanced. Thus the new operating point is reached which has higher load angle value than the previous point in the P-δ curve. The gradual addition of load is possible till the point 2 is reached on the power angle curve where $P = P_{max}$ and any further addition of load will result in increase in rotor angle δ but reduction in output power of the generator In order to compensate the further increase in load demand, load angle δ increases further but the power output of the generator decreases This cumulative process continues which can lead to loss of synchronism of the generator and cause the generator to stall. P_{max} is known as the steady state stability limit of the system which means that it is the maximum power that can be transmitted considering steady state stability criteria and synchronism will be lost if an attempt is made to transmit more power over this limit.

With the change in power transfer the load angle does not change from one value to another instantly First it oscillates due to the generator rotor oscillations because of rotor inertia and then settles to a new operating value if the system gets stable. The equation describing the relative motion of the rotor (load angle δ) with respect to time is known as the swing equation It is a non-linear equation. Considering damping coefficient to be zero, the swing equation is given as ·

$$\frac{2H}{\omega_o}\frac{d^2\delta}{dt^2} = P_m - P_e \tag{4.7}$$

where,

P_e = electrical power output of the generator (p.u.)

P_m = mechanical power input to the generator (p.u.)

H = p.u. inertia constant (in sec)

ω_o = rated angular frequency (rad / sec)

The study of steady state stability of power system involves the study of the dynamics of the system when the rate of application of load is quite slow as compared to the natural frequency

of oscillation of the system Thus a linearized dynamical model of the system can be used for the steady state stability analysis

The swing equation can be linearised around a initial operating point (P_o, δ_o) The linearised equation is given as ·

$$\frac{2H}{\omega_o}\frac{d^2\Delta\delta}{dt^2} = -\left(\frac{\partial P}{\partial \delta}\right)\Big|_{\delta_o}\Delta\delta \qquad (4.8)$$

the roots of this differential equation are given as :

$$p = \pm\left(\frac{\left(-\partial P/\partial\delta\right)|_{\delta_o}}{\dfrac{2H}{\omega_o}}\right)^{\frac{1}{2}} \qquad (4.9)$$

For positive $\frac{\partial P}{\partial \delta}$ i e $\delta < 90°$ (Figure 4 4), the two roots are purely imaginary and form conjugate pair which implies a marginally stable system Thus for steady state stable system, the change in generator output power with respect to change in generator load angle should be positive, i.e $\frac{\partial P}{\partial \delta} \geq 0$ should hold. This implies that for steady state stable operation of generator the value of δ should be less than 90°. At point 2 (Figure 4.4) $\frac{\partial P}{\partial \delta} = 0$ and δ = 90° This point corresponds to maximum steady state stability limit

4.2.2.2 Transient Stability

Transient stability is the stability of the power system to withstand a severe and major disturbance such as a fault The power system is stable in this sense if it does not lose synchronism due to the disturbance. The system comes to a new state after the disturbance It also refers to the maximum flow of power possible through a point without losing the stability with sudden and large changes in the network conditions. The transient stability depends upon the initial conditions of the system and the severity and nature of the disturbance. Since major disturbances can cause large deviation in load angles, non-linear dynamical model of the system is considered for the transient stability studies. The equal area criteria can be used for the transient stability analysis of a single machine infinite bus or two machine system

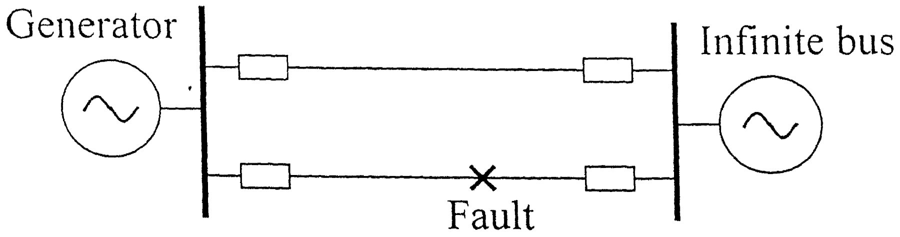


Figure 4.5 : SMIB system with two parallel lines

Figure 4 5 shows parallel lines fed from a finite generator at one end and at the other end connected to an infinite bus A fault occurs in one of the lines. The fault is allowed to exist for some time Then the circuit breakers at both sides of the line operate simultaneously and the faulted line is disconnected In these three conditions i.e pre fault, during fault and post fault conditions the equivalent impedance between the buses changes. Figure 4.6 shows the power angle curves for these three conditions. The equivalent impedance is minimum at normal operating point. During the fault condition the impedance increases and hence the operation goes to the curve corresponding to this condition. During this condition the output of the generator decreases and become less than the mechanical power input (P_m). Thus the rotor accelerates The kinetic energy gained by the rotor during this period is given by the area A1. After the application of the circuit breakers the equivalent impedance slightly decreases and hence the operation goes to curve corresponding to post fault condition. Now the output of the generator increases and becomes more than P_m and the rotor decelerates till the speed becomes equal to the speed of the infinite bus The energy loss by the rotor is given by area A2 For the transient stability, following condition should hold :

$$\text{Area A1} \leq \text{Area A2} \qquad (4\ 10)$$

In Figure 4.6,

δ_0 is load angle when the fault occurs

δ_c is load angle when circuit breaker operates

δ_m is maximum angle excursion

δ_c corresponds to critical clearing angle, when area A1 = area A2.

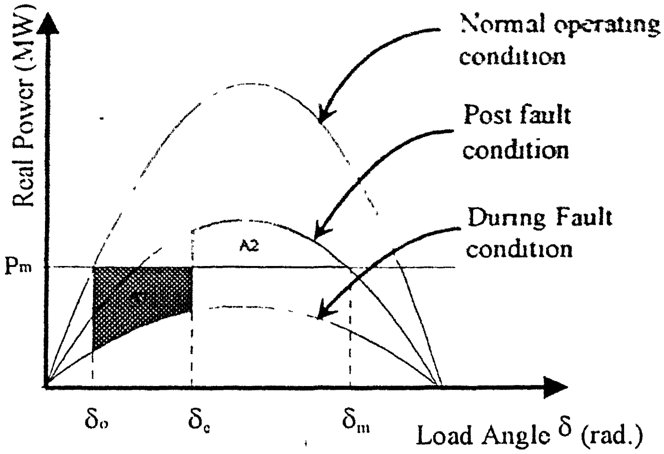


Figure 4 6 P-δ curve for pre, during and post fault condition

Steady state stability and transient stability can both be seen as angular stability problem. These stabilities are mainly concerned with maintaining synchronous operation of various generating plants subjected to a disturbance These stabilities can be used as the dynamic criteria for the ATC calculation Considering both the stability criteria ensures reliable system operation under small slow changing disturbance like load change and fast severe disturbance like faults.

In this chapter different static and dynamic criteria which can be used for ATC determination were described. In the static criteria line thermal limit, bus voltage magnitude limit, generator real and reactive power output limit and voltage collapse limits were taken. Where as, under dynamic criteria steady state stability limit and transient stability limit were discussed.

Chapter 5

Methods and Mathematical Formulation for ATC Determination

In the previous chapter, the static and dynamic criteria for the ATC determination were discussed The methods used for the ATC calculation using these criteria are described in this chapter. Mathematical formulations of the methods are also presented The ATC which is calculated considering static criteria has been called 'Static ATC' and with the dynamic criteria as 'Dynamic ATC'. Methods for the static ATC and the dynamic ATC determination are presented in the following sections.

5.1 Static ATC methods

Static criteria are analysed in two parts First thermal limits, bus voltage magnitude limits and generator reactive power limits are analysed through the AC power flow method. Second voltage collapse conditions are analysed through continuation power flow method. Criteria are checked for both the pre- and post- contingency conditions. (n-1) contingency is taken in this work, i e contingency considering the outage of one element at a time.

5.1.1 Newton Raphson load flow method

A load flow analysis determines the state vector for given control and disturbance variables. State vector is the minimum set of variables required to represent the state of the system. The voltage magnitude and the phase angle at the load bus and the reactive power generation and the phase angle at the P-V bus are included in the state vector for the power system Disturbance variables interpret changes in the loads of the system. Control variables are those on which the system operator has control. They are real power generation and voltage

magnitude at the P-V buses. Once the state vector is determined, bus power and line flows can be calculated First the network equations are established and then a suitable mathematical technique is used to find the solution of the equations.

The network equations are the non-linear algebraic equations. In polar form they are given as.

$$P_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \text{ (for all buses except slack bus)} \qquad (5.1)$$

$$Q_i = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \qquad \text{(only for P-Q buses)} \qquad (5\ 2)$$

where,

Bus power at bus i , $S_i = P_i + jQ_i$ (5.3)

Bus voltage at bus i, $\overline{V_i} = V_i \angle \delta_i$ (5.4)

(i, j)[th] element of Y_{bus} matrix, $\overline{Y_{ij}} = Y_{ij} \angle \theta_{ij}$ (5.5)

The above equations are solved using Newton Raphson method.

First the bus voltages and voltage phase angles are calculated and then the line flows for particular set of system conditions are determined. Repetitive power flow is used, with increasing real and reactive power load with constant power factor at the sink bus and the corresponding real and reactive power generation at the source bus, till line thermal loading limits or bus voltage magnitude limits are hit. The Newton Raphson load flow method automatically takes into account the real and reactive power limits of the generator The maximum power flow at which one of the thermal or bus voltage limit is hit is taken to be the transfer capability of the system considering these constraints. These limits are the static criteria (section 4.2 1) which are mathematically represented as :

$$|P_T| \le P_{T\max} \qquad (5.7)$$

$$V_{b\min} \le V_b \le V_{b\max} \qquad (5.8)$$

$$P_g \le P_{g\max} \qquad (5.9)$$

$$Q_{g\min} \le Q_g \le Q_{g\max} \qquad (5.10)$$

5.1.1 Continuation power flow method

The continuation power flow method is used to find a continuum of power flow solutions starting with the base case condition and leading to the steady state voltage stability limits for

a given load change scenario. The main feature of this method is that it remains well-conditioned at and around the critical point [20]. This critical point is the voltage instability point at which system jacobian matrix becomes singular and thus Newton Raphson method diverges

Continuation power flow method uses reformulated power flow equations A new parameter called the load parameter (λ) is inserted in the power flow equation which is used for incremental increase of real and reactive power at different buses The value of λ lies between 0 and $\lambda_{critical}$ $\lambda = 0$ corresponds to the base case power and $\lambda = \lambda_{critical}$ corresponds to bus critical power, ie power corresponding to voltage instability point

Continuation power flow employs a predictor corrector scheme to find a solution path of a set of reformulated power flow equations. It starts from a known solution and uses a tangent predictor to estimate a subsequent solution corresponding to a different value of load parameter This estimate is then corrected using the same Newton-Raphson technique employed by a conventional power flow. The reformulated power flow equation for each bus i of an n bus system is given as :

$$0 = P_{Gi} - P_{Li} - P_{Ti} \tag{5.11}$$

$$0 = Q_{Gi} - Q_{Li} - Q_{Ti} \tag{5.12}$$

where,

real power generation $$P_{Gi} = P_{Gi0}(1 + \lambda k_{Gi}) \tag{5.13}$$

reactive power generation $$Q_{Gi} = Q_{Gi0} \tag{5.14}$$

real power load $$P_{Li} = P_{Li0} + \lambda(k_{Li} S_{base} \cos \psi_i) \tag{5.15}$$

reactive power load $$Q_{Li} = Q_{Li0} + \lambda(k_{Li} S_{base} \sin \psi_i) \tag{5.16}$$

transmission line real power $$P_{Ti} = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{5.17}$$

transmission line reactive power $$Q_{Ti} = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \tag{5.18}$$

V_i, V_j, Y_{ij}, δ_i, δ_j, θ_{ij} are same as defined in Equation 5 3, 5.4 and 5.5

P_{Gi0}, Q_{Gi0}, P_{Li0}, Q_{Li0} are the original real and reactive power generation and load at bus i

k_{Gi} is a constant used to specify the rate of change in generation as λ varies

k_{Li} is a constant to specify the rate of load change at bus i as λ varies

ψ_i is a power factor angle of load change at bus i

S_{base} is base MVA of the system

Here a real and reactive power participation factor (Pfp_i, Pfq_i) are used in place of k_{Li} and ψ_i they are given as :

$$Pfp_i = k_{Li} \times \cos \psi_i \tag{5.19}$$

$$Pfq_i = k_{Li} \times \sin \psi_i \tag{5 20}$$

The load change scenario is given by pair of source and sink buses corresponding to the transmission path for which the ATC is to be calculated. The continuation power flow method produces the continuos power flow solutions for the increasing load and generation power conditions at these sink and source buses This method provides the maximum value of load parameter corresponding to the voltage collapse point. The maximum real and reactive power consumption at the sink bus considering voltage collapse criteria is calculated using Equation 5 21 and Equation 5.22.

$$P_{i\max} = P_{Li0} + Pfp_i \times \lambda_{\max} \times S_{base} \tag{5 21}$$

$$Q_{i\max} = Q_{Lio} + Pfq_i \times \lambda_{\max} \times S_{base} \tag{5 22}$$

where,

$P_{i\max}$, $Q_{i\max}$ = maximum real and reactive power consumption at bus i corresponding to voltage collapse point in MW, Mvar

The bus having maximum rate of change of voltage and minimum voltage at the collapse point is considered as the critical bus in the system.

5.2 Dynamic ATC methods

The ATC which is calculated considering system dynamic criteria is called Dynamic ATC Steady state stability is taken as dynamic criteria for evaluation of the dynamic ATC A mathematical formulation and methods for computing power transfer limit using this criteria are discussed in following sections.

5.2.1 Steady state stability analysis

In this work, single machine infinite bus system (Figure 4.3) is considered for the steady state stability analysis. This system consist of a single generator connected to a large system through a transmission line. The large system network is represented by an infinite bus The equivalent circuit for this system is shown in Figure 5.1. The generator is represented by a voltage source behind its transient reactance using classical model Resistances are neglected in the system.

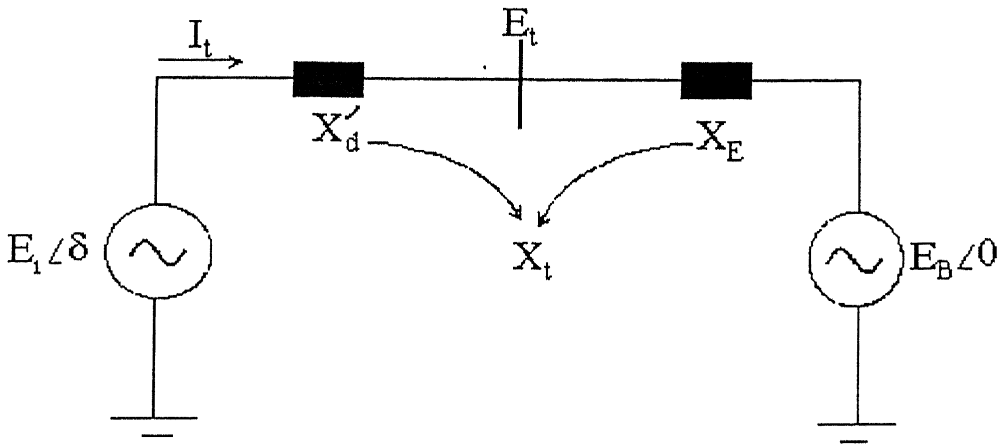


Figure 5.1 : Equivalent circuit for SMIB system

The steady state stability analysis is divided into three steps .

1. Calculation of load angle
2. Characteristic equation and eigen value determination
3. Time domain analysis for load angle and rotor angular frequency

For each power transfer condition, P and Q are known at generator terminal and generator terminal voltage is assumed to be 1 p.u. The generator direct axis reactance, the inertia constant and the damping torque coefficient are considered to be known.

5.2.1.1 Calculation of the load angle

Starting from the initial condition, the power transfer is increased with constant increments. The load angle is calculated for the new power transfer condition. For the steady state stability, the load angle should be less than 90° A mathematical formulation for calculating load angle is given below.

The current flow through the network is given as,

$$\bar{I}_t = \frac{(P + jQ)^*}{\bar{E}_t^*} \qquad (5\ 23)$$

Generator internal voltage and infinite bus voltage are given as respectively,

$$\overline{E}_i = \overline{E}_t + jX_d' I_t \quad (5\ 24)$$

$$\overline{E}_B = \overline{E}_t - j(X_t - X_d')\overline{I}_t \quad (5\ 25)$$

thus the load angle is calculated as,

$$\delta_o = \angle(E_i) - \angle(E_B) \quad (5\ 26)$$

the power transfer condition at which load angle reaches to 90°, is considered as the steady state stability power transfer limit Other criteria for steady state stability power transfer limit calculation are eigen value analysis and time domain analysis The mathematical formulation of these methods is discussed in next two sections

5.2.1.2 Characteristic equation and eigen value determination

Considering generator internal voltage as reference, current I_t flowing through the network is given as

$$\overline{I}_t = \frac{E_i\angle 0° - E_B\angle -\delta}{jX_t} = \frac{E_i - E_B(\cos\delta - j\sin\delta)}{jX_t} \quad (5\ 27)$$

Thus, the complex power flow is

$$S = P + jQ = \overline{E}_i\overline{I}_t^* = \frac{E_iE_B\sin\delta}{X_t} + j\frac{E_i(E_i - E_B\cos\delta)}{X_t} \quad (5\ 28)$$

With stator resistance neglected, air-gap power (P_e) is equal to the terminal power (P) And in per unit, the air gap torque is equal to the air-gap power Hence,

$$T_e = P = \frac{E_iE_B}{X_t}\sin\delta \quad (5\ 29)$$

Linearizing the above equation around initial operating condition (P_o, δ_o),

$$\Delta T_e = \frac{\partial T_e}{\partial\delta}\Delta\delta = \frac{E_iE_B}{X_t}\cos\delta_o(\Delta\delta) \quad (5\ 30)$$

the swing equation can be written as,

$$\Delta\dot{\omega} = \frac{1}{2H}(T_m - T_e - K_D\Delta\omega) \quad (5\ 31)$$

$$\dot{\delta} = \omega_b\Delta\omega \quad (5\ 32)$$

where, ω_b is rated angular frequency

T_m is mechanical torque input

K_D is Damping coefficient

H is Inertia constant

Linearising the swing equation and substituting for ΔTe.

$$\Delta\dot{\omega}=\frac{1}{2H}(\Delta T_m-K_S\Delta\delta-K_D\Delta\omega) \tag{5.33}$$

$$\Delta\dot{\delta}=\omega_b\Delta\omega \tag{5.34}$$

where synchronising torque coefficient (Ks) is given as,

$$K_S=\frac{E_tE_B}{X_t}\cos\delta_o \tag{5.35}$$

Writing the equation in vector matrix form,

$$\begin{bmatrix}\Delta\dot{\omega}\\ \Delta\dot{\delta}\end{bmatrix}=\begin{bmatrix}\frac{-K_D}{2H} & \frac{-K_S}{2H}\\ \omega_o & 0\end{bmatrix}\begin{bmatrix}\Delta\omega\\ \Delta\delta\end{bmatrix}+\begin{bmatrix}\frac{1}{2H}\\ 0\end{bmatrix}\Delta T_m \tag{5.36}$$

the state matrix is given as,

$$\mathbf{A}=\begin{bmatrix}\frac{-K_D}{2H} & \frac{-K_S}{2H}\\ \omega_o & 0\end{bmatrix} \tag{5.37}$$

the elements of state matrix are dependent upon the system parameters K_D, H, X_t and initial operating condition represented by the values of E_t and δ_o

Thus the characteristic equation is given as,

$$(\mathbf{A}-\lambda\mathbf{I})=0 \tag{5.38}$$

If λ represent the eigen value, then the above characteristic equation can be written as,

$$\lambda^2+2\zeta\omega_n\lambda+\omega_n^2=0 \tag{5.39}$$

where,

undamped natural frequency $$\omega_n=\sqrt{K_S\frac{\omega_o}{2H}} \tag{5.40}$$

damping ratio $$\zeta=\frac{1}{2}\frac{K_D}{\sqrt{K_S 2H\omega_o}} \tag{5.41}$$

5.2.1.3 Determination of time response of load angle and rotor angular frequency

For the above characteristic equation (Equation 5.38), the right (φ) and left (ψ) eigen vectors can be calculated as,

$$(\mathbf{A}-\lambda\mathbf{I})\varphi=0 \tag{5.42}$$

$$\phi=\varphi^{-1} \tag{5.43}$$

the time response is given as,

$$\begin{bmatrix} \Delta\omega(t) \\ \Delta\delta(t) \end{bmatrix} = \begin{bmatrix} \phi_{11} & \phi_{12} \\ \phi_{21} & \phi_{22} \end{bmatrix} \begin{bmatrix} c_1 e^{\lambda_1 t} \\ c_2 e^{\lambda_2 t} \end{bmatrix} \qquad (5\ 44)$$

where,

$$\begin{bmatrix} c_1 \\ c_2 \end{bmatrix} = \begin{bmatrix} \psi_{11} & \psi_{12} \\ \psi_{21} & \psi_{22} \end{bmatrix} \begin{bmatrix} \Delta\omega(0) \\ \Delta\delta(0) \end{bmatrix} \qquad (5.45)$$

vector $\begin{bmatrix} \Delta\omega(0) \\ \Delta\delta(0) \end{bmatrix}$ gives the variation of rotor frequency and load angle time t = 0

5.3 Data required for ATC determination

The accuracy of the ATC calculation depends upon the accuracy of the data available. The data should be reliable and up-to-date. Following data are required for ATC calculation :

- System configuration
- Generators real and reactive power output
- Real and reactive power loads
- Transmission lines and transformers data
- Generators real and reactive power limit
- Lines thermal limit
- Bus voltage minimum and maximum limits
- Reactive power sources
- Generator data : Inertia constant, damping coefficient and direct axis reactance

5.4 ATC determination model

5.4.1 Static ATC determination model

The criteria used for static ATC determination model are :

1 Line thermal limit
2. Bus voltage magnitude limit
3 Voltage collapse limit
4. Generator real and reactive power limit

The tools used for the analysis of these criteria in this model are :

1. Newton Raphson load flow method
2. Continuation power flow method

The steps involved in this model to calculate ATC are listed below Figure 5.2 shows the flow chart for the procedure.

Step 1

Base case selection . Determination of ATC depends upon the condition of the system above which ATC is to be calculated. This condition is taken as the base case condition for the system Thus the first step is the selection of base case condition for which all the criteria considered for ATC determination should be satisfied.

Step 2

Transmission path selection : ATC is calculated for a given transmission path. This transmission path is defined by a pair of source and sink buses. Thus a transaction path is chosen for which ATC is to be calculated.

The selected base case condition and the transmission path are used as an input data to the methods for further calculation of the transfer capability.

Step 3

TC11 Determination : For the selected transmission path, loading at the sink bus is increased with corresponding increase in generation at source bus. Repetitive power flow is done with incremental increase of power transfer through selected transmission path till line thermal limit or bus voltage magnitude limit violation takes place in the system. The amount of power flow between the source and sink buses at this condition is taken as the transfer capability TC11. Thus TC11 is the transfer capability of the transmission line with all element present in the system considering thermal limit, bus voltage limit and generator real and reactive power limit

Step 4

TC12 Determination : Starting from the base case condition, maximum load parameter is calculated corresponding to voltage instability point. The load and the generation are varied at the sink and source buses of the selected transmission path. The real and reactive power at the

sink bus corresponding to maximum load parameter is taken as the transfer capability TC12 Thus TC12 is the transfer capability of the transmission path with all elements present in the system considering voltage collapse condition

Step 5

TC1 Determination : TC1 gives the transfer capability of the transmission path with all element present in the system. It is calculated as,

$$TC1 = \text{Minimum}\ \{TC11,\ TC12\} \tag{5.46}$$

Step 6

TC21 Determination : It is the minimum of the transfer capability calculated for different contingency conditions considering thermal and bus voltage magnitude limits. For each contingency condition transfer capability is calculated using repetitive power flow with incremental increase of power transfer through the selected transmission path The minimum of these transfer capabilities is taken as TC21

Step 7

TC22 Determination : It is the minimum of the transfer capability calculated for different contingency conditions considering the voltage collapse criteria. For each contingency condition power transfer capability of the selected transmission path is calculated corresponding to maximum load parameter at voltage instability point. While performing continuation power flow, power transfer is only varied at the selected transmission path Minimum of these transfer capabilities is taken as TC22.

Step 8

TC2 determination · TC2 gives the transfer capability of the transmission path considering different contingency conditions. It is calculated as,

$$TC2 = \text{Minimum}\ \{TC21,\ TC22\} \tag{5.47}$$

Step 9

TTC determination . Total transfer capability (TTC) of the transmission path is calculated as,

$$TTC = \text{Minimum}\ \{TC1,\ TC2\} \tag{5.48}$$

Step 10

ATC determination : ATC for the transmission path is given as,

$$ATC = TTC - \text{Base case power transfer on transmission path} \quad (5.49)$$

This static ATC determination model provides a step by step calculation procedure This is useful in understanding each component of the ATC. Step 1 and 2 set the input condition for the calculation of transfer capabilities. The next steps calculate transfer capability for each limiting condition for pre and post contingencies. TTC is the minimum of these transfer capabilities Then ATC is calculated using Equation 5.49

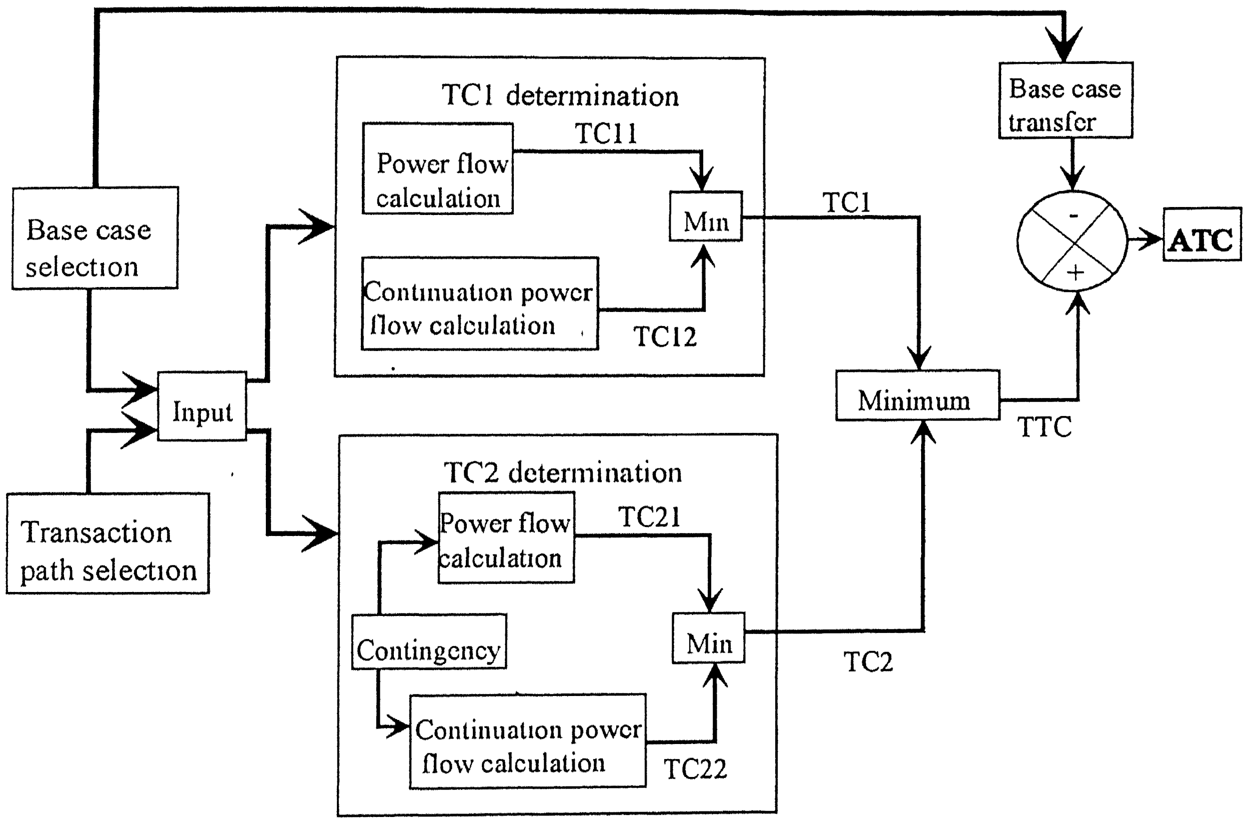


Figure 5.2 : Flow chart for ATC determination

5.4.2 Dynamic ATC determination model

The model for the dynamic ATC determination consider the steady state stability criteria. The steps involved in it are discussed as follows.

Step 1

Initial condition : For the selected initial power transfer condition, load angle (δ) of the generator should be less than 90° with an appreciable margin This implies that system is not operating on the verge of steady state stability and their remain still some transfer capability in the system considering steady state stability.

Step 2

Steady state stability limit calculation : For the selected initial condition, the power transfer is increased with small increments For each increased power transfer conditions the load angle, the eigen value and the time response of load angle are calculated. The steady state stability power transfer limit is the power transfer condition at which the load angle of the generator reaches 90°. Two more criteria can also be used for steady state stability limit evaluation. These are

1 When the real part of an eigen value of characteristic equation (5.38) is approaching zero.
2 When the time response of δ due to a change in power transfer have a continuous increasing slope and it does not settle to a stable operating value

The power transfer condition at which the load angle of the generator reaches 90° is taken as the total transfer capability of the transmission path for steady state stability limit. Thus dynamic ATC for steady state stability is given as,

$$ATC = TTC - \text{initial power transfer} \qquad (5.50)$$

In this chapter methods used for ATC calculation were described. The models were developed for the static and the dynamic ATC determination. The static ATC determination model was tested on Iceland 220kV system and Indian UPSEB 400kV system. The dynamic ATC determination model was tested on single machine infinite bus system. The results are discussed in the following chapters.

Chapter 6

Determination of ATC for the Icelandic 220kV system

6.1 The Icelandic Grid

Icelandic power system (Figure 6.1) is a small and isolated system with total load of 1325 MW and the generation of 1366 MW in the year 2000 [21] The difference between total generation and load accounts for the transmission losses in the system. The principal amount (two third of the country's entire production) of electrical energy in Iceland is produced by hydro plants in the southern part of Iceland. The major generating units of Iceland grid and their capacity is shown in Table 6 1. The largest group of customers are the industrial sector, including two aluminium smelters and ferro-silicon plants at ISAL and NAL and the loads of the capital Reykjavik The transmission levels used in Icelandic system are 220kV, 132kV, 66kV and 33kV.

Name	MW	GWh (1999)
Burfell	217	2195
Sigalda	120	786
Hrauneyafoss	205	1174
Irafoss	68	262
Blanda	150	927
Laxa	28	167

Table 6.1 · The main generating units and their capability

The generating capacity and transmission network are enough to satisfy the present need of the Islanders. But in a way, it will be also interesting to have the knowledge of further power

transfer capability in the network which will be beneficial for the distribution of the load demand in the future The 220kV network part of this Icelandic grid is taken as a study system for a ATC determination here

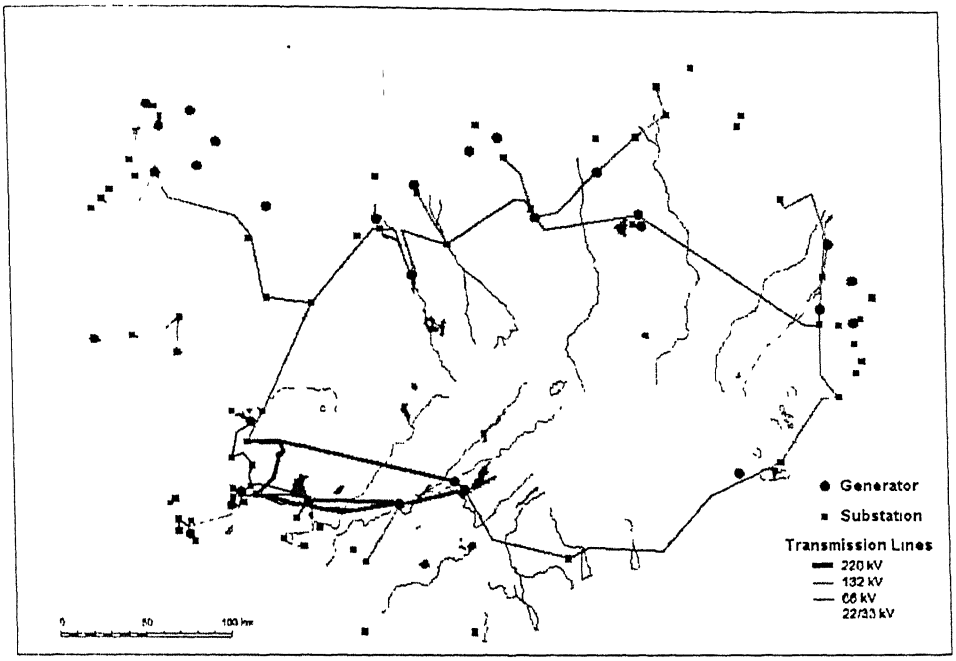


Figure 6.1 : The Icelandic power system

6.2 The Icelandic 220 kV system

The study system for this work is derived from the Icelandic grid It consists of the 220kV network of Iceland grid (Figure 6.2). Other lines, small loads and generators have been omitted. This part of network lies in the south-west part of country, where energy production is 75% of the total production and consumption is 70% of the total consumption. Thus principal part of the generation and the consumption of the country is in this part of the network. It consist of 13 buses and 18 transmission lines and transformers.

Generating Unit	Generation (MW)	Load centres	Consumption (MW)
Hrauneyjafoss	205	**ISAL**	275
Burfell	217	**NAL**	140
Sigalda	120	**Burfell**	32
Irafos	68		
TOTAL	614	*TOTAL*	447

Table 6 2 : Generation and consumption in the Iceland 220kV system

The main generating stations are Hrauneyjafoss, Burfell, Sigalda and Irafos and the main load centres are ISAL and NAL which takes the load of two Aluminium factories (Table 6 2). A reasonable amount of load, 32 MW, is taken to be connected at Burfell which represent the distributed loads near Burfell. Hrauneyjafoss is one of the large generating unit in the system with a generating capacity of 210 MW, 60 Mvar. It is taken as slack bus for the system. The system is assumed to be deregulated system in which every customer is free to buy power from any power producer But the transaction should abide the security and the reliability criteria Thus it is considered to be beneficial to have the knowledge of the ATC in the system The ATC is calculated for the transmission path between generating unit at Burfell and the load centre ISAL This transmission path takes into account the power transfer between the biggest generating station Burfell and the largest power consumer ISAL. This path can provide a good range of increase in power transfer for ATC determination.

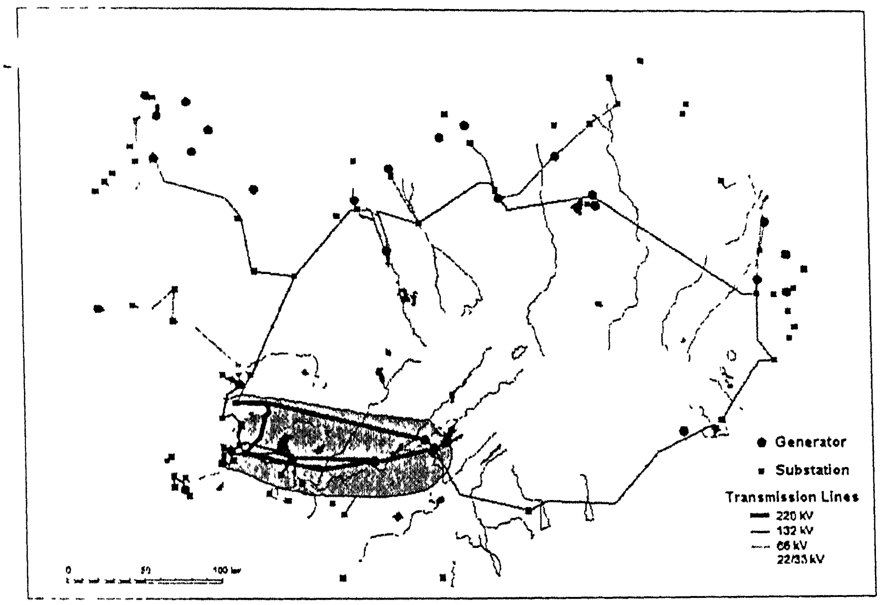


Figure 6 2 : Iceland 220kV network region

6.3 The base case

A selection of correct base case is very important in the determination of ATC. At this condition all the criteria for the ATC determination should be satisfied. The system considered here is shown in Figure 6.3. Since it is a part of the Icelandic grid in which 132kV, 66kV and 33kV lines and buses have been neglected some adjustment is made to get a required base case condition. The load centres of ISAL and NAL take power from generating

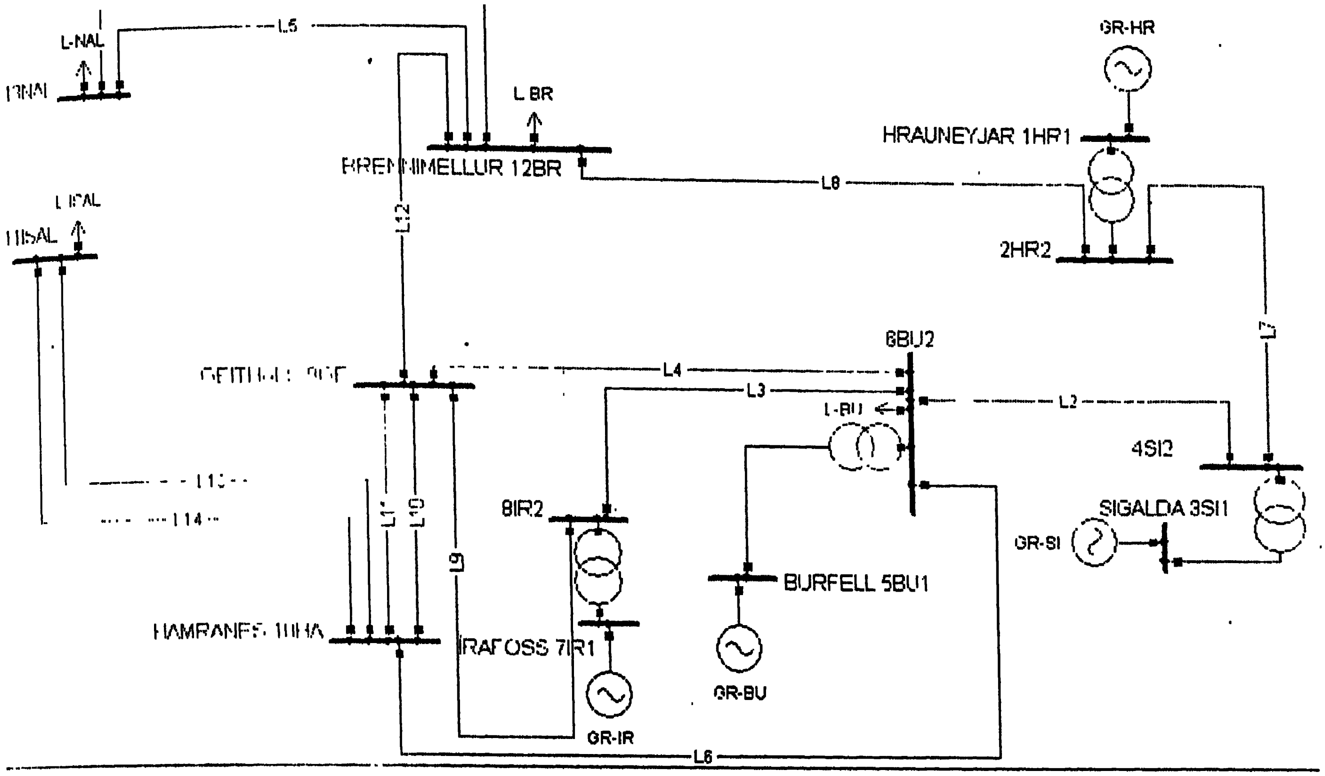


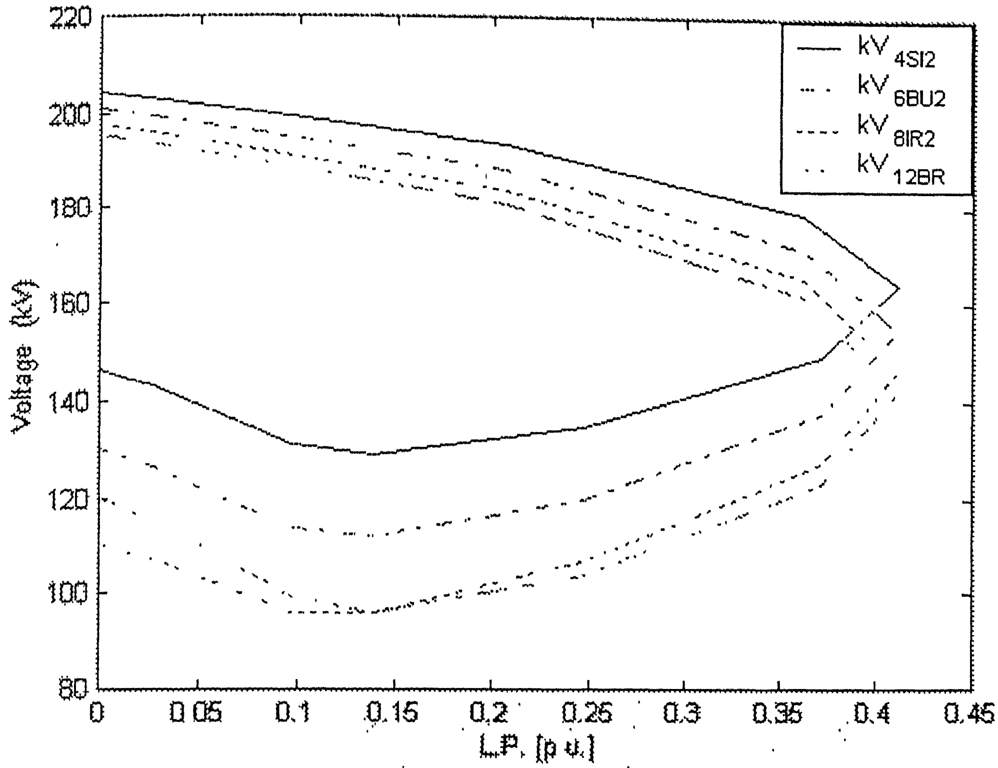
Figure 6.3 : Iceland 220kV power system

units at northern part of Iceland like Blanda, which is to be reduced from actual loading condition at these buses. Some adjustment at generation sector have also been made to neglect the power transfer to the northern part and to some small load centres. The generation and load condition for the selected base case are given in Table 6.3.

Generating Unit	Generation (MW)	Load centres	Consumption (MW)
Hrauneyjafoss	140	**ISAL**	210
Burfell	109	**NAL**	78
Sigalda	120	**Burfell**	32
Irafos	68		
TOTAL	**437**	***TOTAL***	**310**

Table 6.3 : Main generation and consumption in the study system

At the selected base case condition the limiting values for line loading and bus voltage magnitude are given in Table 6.4 and P-V curve for different buses is shown in Figure 6.4. The maximum line loading is found at line L9 which is the 75% of its thermal limit. The minimum voltage occurs at bus 11 ISAL which is 201kV. It is within the bus voltage limit (230kV-190kV).



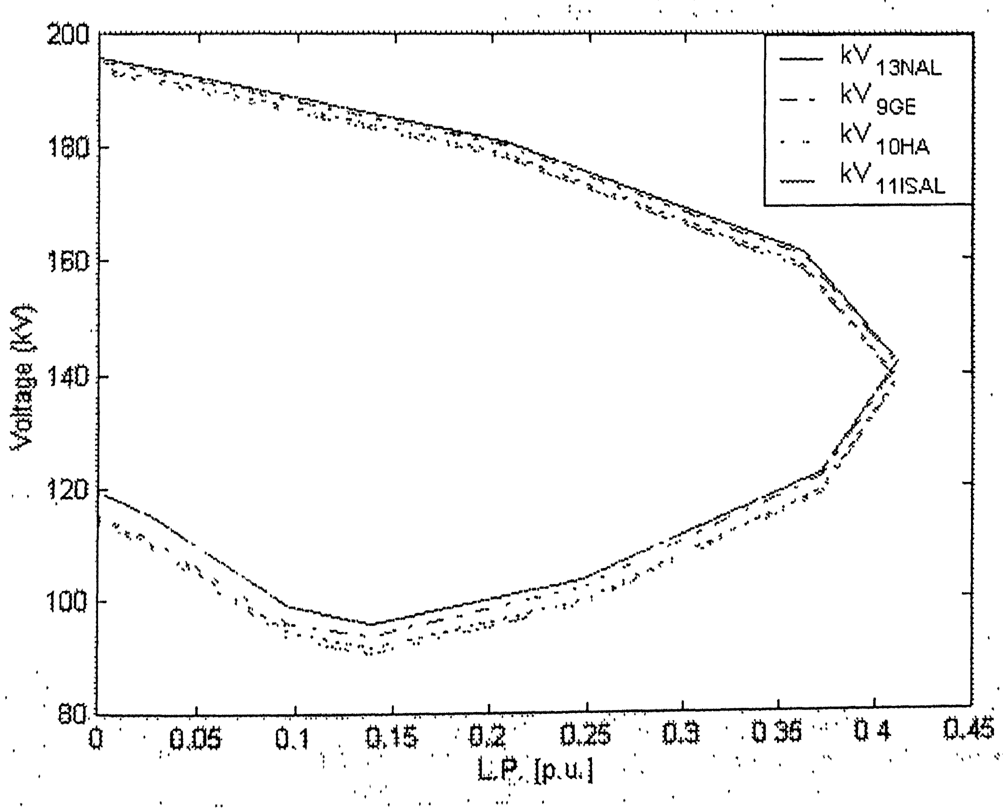


Figure 6.4 : P-V curve at load buses for base case condition

The P-V curves show a good margin from the voltage collapse point. The base case condition corresponds to the zero value of load parameter (L.P.) where as the voltage collapse point occurs at L P = 0 4125p.u The base value for load parameter is 100MVA.

The selected base case satisfy the ATC determination criteria with a reasonable margin. Thus the system contains some extra power transfer capability which could be utilised by market participants in the system This available power transfer capability is calculated considering the transmission path between generating unit at Burfell and the load centre ISAL

[illegible]	[illegible]
Maximum line loading	At line L9, 75 0 % of thermal limit
Minimum Bus voltage magnitude	At bus 11 ISAL, 201kV

Table 6 4 : Limiting values for base case condition

6.4 Calculation of ATC

For the selected base case condition and transmission path in the Icelandic 220kV system the ATC is to be calculated The process will proceed according to the procedure described in Section 5 4

6.4.1 The TC1 determination

Starting from the base case condition, the load at ISAL is increased in incremental steps with the corresponding increase in generation at Burfell. Both real and reactive power is varied assuming constant power factor at ISAL. At the loading condition of 237MW and 104.5Mvar at ISAL, limiting condition is reached since for further increment of power transfer, load-flow diverges This gives the TC11 (Table 6.5).

	P	Q	Limiting condition
TC11	237MW	104.5 Mvar	Load-flow diverges for higher loading condition

Table 6.5 : TC11 determination

For the calculation of TC12 , continuation power flow method is used to find the maximum load-parameter (λ_{max}) at saddle node bifurcation point starting from the base case condition. Figure 6.5 shows the voltage profile at different buses. The variation of load and generation is considered only at buses ISAL and Burfell respectively. Table 6.6 shows the result for TC12

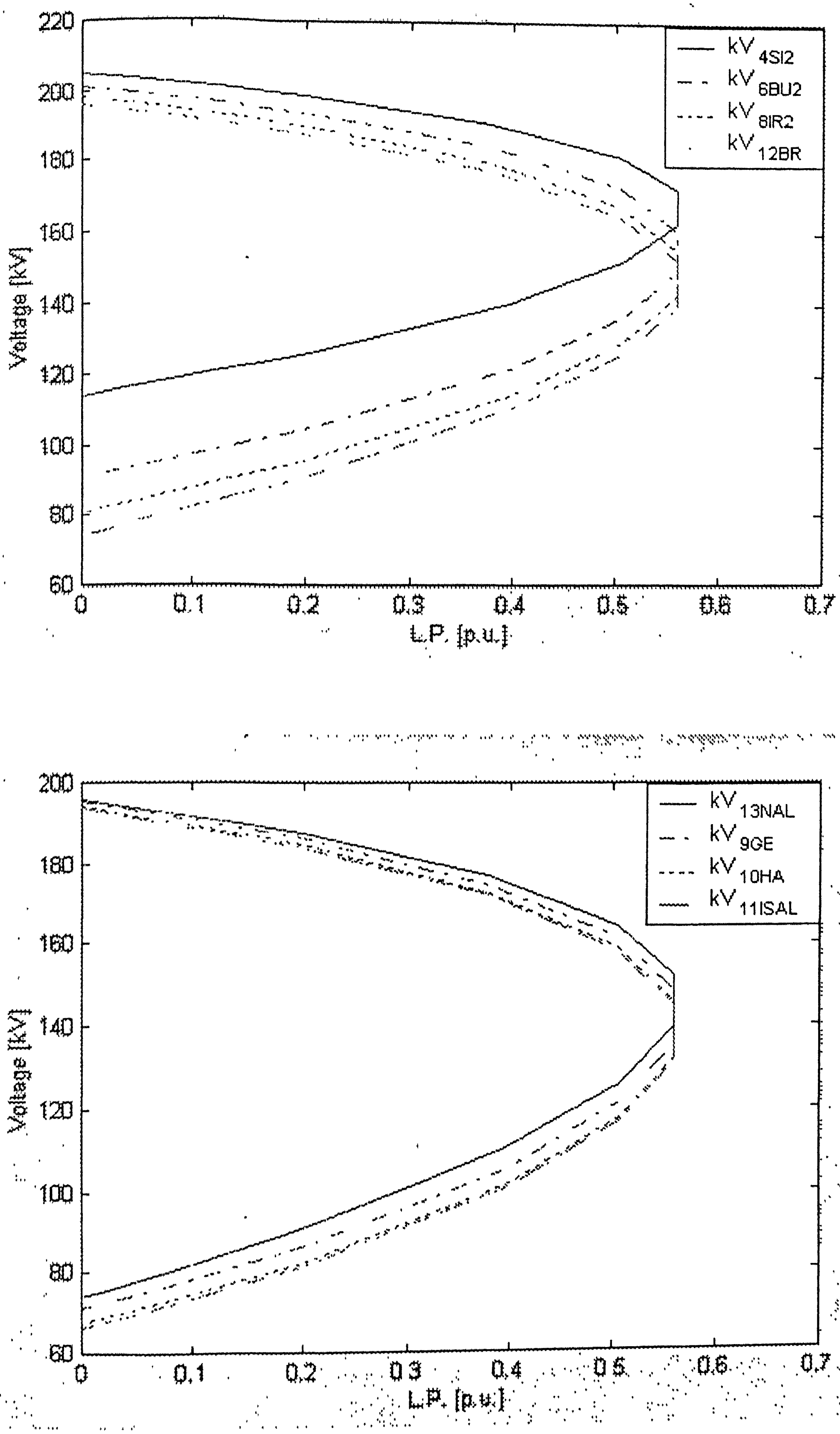


Figure 6.5 · P-V curve at load buses with varying power transfer on selected transaction path

	P	Q	λ_{max}	Critical bus	$V_{critical\ bus}$
TC12	327MW	140 Mvar	0.5588	11 ISAL	144 7kV

Table 6.6 : TC12 determination

The maximum load-parameter found was 0.55880. At this point the minimum voltage occurs at bus 11 ISAL i e. 144 7kV Thus TC12 is the loading condition corresponding to maximum load-parameter which comes to be 327.34 MW and 140.29 Mvar Hence

TC1 = Minimum { TC11, TC12 } = 237 MW and 104.5 Mvar

This is the transfer capability with all elements present in the system.

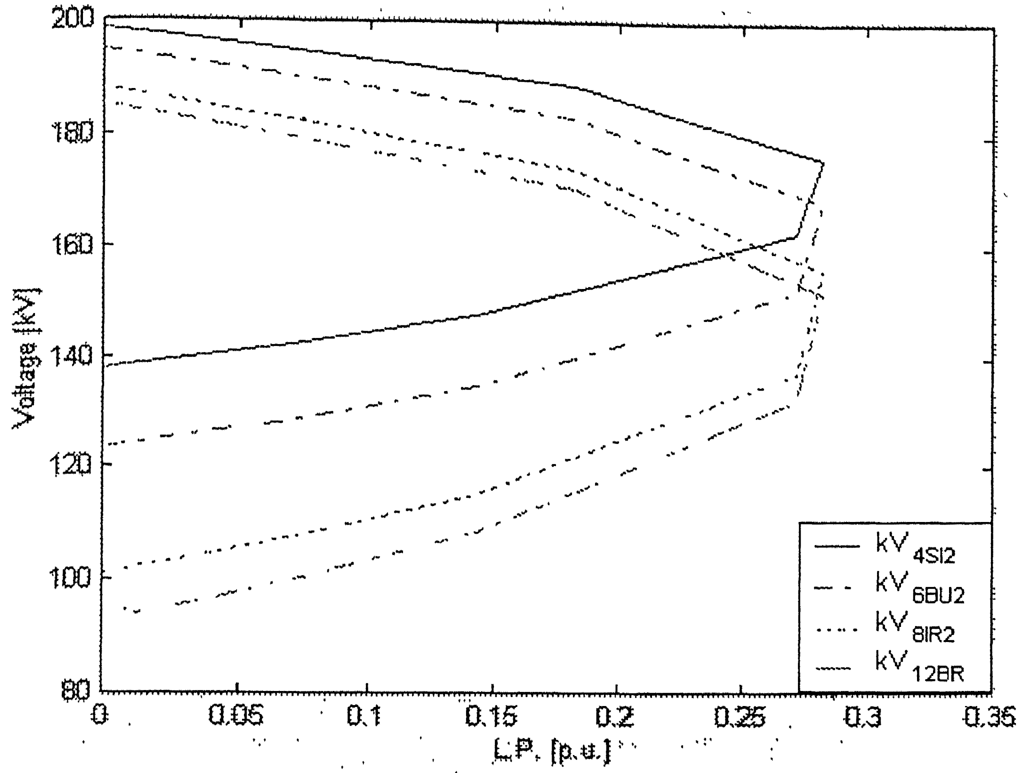
6.4.2 The TC2 determination

For the determination of TC2, line outage contingencies are considered Generator outage condition are neglected because of two reasons. Firstly, the smallest generating unit i.e. Irafoss is generating 68 MW at the base case condition In the case of outage of this generator the loss in generation will be compensated by the slack bus which itself is having limited generating capacity and therefore could not fulfil this generation loss. Since the generators are not big enough to compensate the generation loss in this system thus generation outage contingency is neglected as a criteria for the ATC determination. Secondly, Line outage contingencies are frequent in the system as compared to generator outage.

Outage of lines L1, L3, L4, L5, L6, L7 and L12 are taken for determination of TC2 For each line outage condition, with incremental load and generation increase at ISAL and Burfell respectively, the transfer capability is calculated (Table 6.7) Thus TC21 which is minimum of transfer capability for different line outages comes out to be 215 MW and 92.5 Mvar for the outage of line L4.

Contingency (Line)	Transfer Capability		Limiting condition
	P (MW)	Q (Mvar)	
L5	237	103.5	Load-flow diverges
L1	237	103.5	Load-flow diverges
L12	235	102.5	Load-flow diverges
L7	236	103.0	Load-flow diverges
L6	217	93.5	Load-flow diverges
L4	215	92.5	Maximum line limit at L9
L3	223	96.5	Load-flow diverges

Table 6.7 : Transfer capability for contingency condition considering thermal and voltage limit



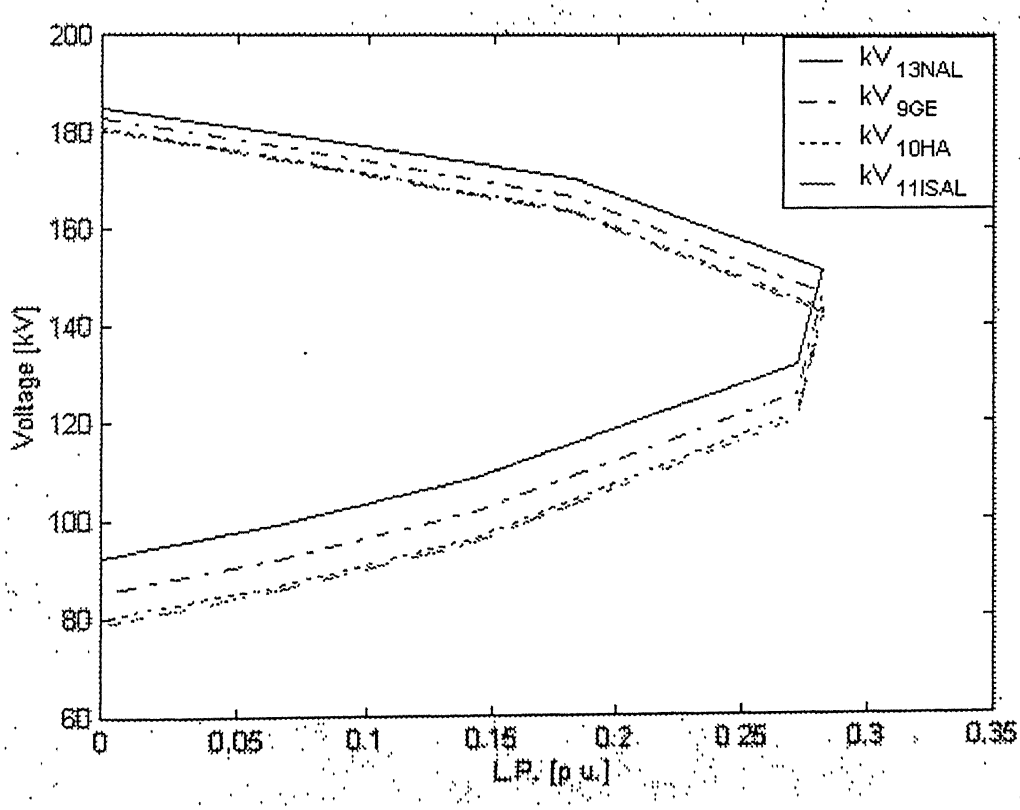


Figure 6.6 . P-V curve at load buses for the critical contingency (L6)

For the determination of TC22, transfer capabilities are calculated for different line outages taking voltage collapse criteria. Continuation power flow is used for different line outages Table 6 8 shows the maximum load-parameter and the corresponding transfer capability for different line outages conditions Bus 11 ISAL is seen to be the critical bus in every condition since it is the maximum loaded bus in the system with no extra reactive power support Voltage corresponding to voltage instability point at the critical bus is also shown in Table 6 8

Contingency (Line)	λ_{max} (p.u.)	Transfer capability		$V_{critical\ bus}$ (kV)
		P (MW)	Q(Mvar)	
L5	0 55758	327.09	140.18	144.50
L1	0.55758	327 09	140.18	144.50
L12	0.55156	325.82	139.64	142.52
L7	0.51182	317 48	136.06	138.71
L6	0.28191	269.20	115 37	142.43
L4	0 52896	321 08	137.60	140.68
L3	0 55324	326.18	139.79	143 40

Table 6.8 : Transfer capability for contingency condition considering voltage collapse limit

Figure 6.6 shows the voltage profile at the load buses for the contingency of line L6 This is the critical contingency since it corresponds to the minimum transfer capability value.
Thus TC22 which is minimum of transfer capability for different line outages considering voltage collapse criteria comes out to be 269.20 MW and 115.37 Mvar. Hence TC2 is calculated as,

$$\boxed{TC2 = \text{Minimum}\{TC21, TC22\} = 215.0\ \text{MW}, 92.5\ \text{Mvar}}$$

This is the transfer capability of the system with the consideration of contingency conditions

6.4.3 The TTC determination

The total transfer capability of the system considering thermal limit, voltage magnitude limit and voltage collapse criteria for both pre and post contingency condition is given as .

$$\boxed{TTC = \text{Minimum}\{TC1, TC2\} = 215.0\text{MW and } 92.5\text{Mvar}}$$

6.4.4 The ATC determination

Available transfer capability for the transaction path between Burfell and ISAL in the Icelandic 220kV system is calculated as ·

ATC = TTC – Base case transfer for Burfell-ISAL transaction path = 5 MW and 2.5 Mvar

ATC = 5.0 MW and 2.5 Mvar

Table 6 9 shows the summary of results ATC calculated comes out to be 5 MW, 2.5 Mvar which indicate that ISAL already utilise power from Burfell near to the capability of this transaction path. Thus ISAL cannot buy further more than 5 MW from the Burfell to hold the system operation under security limits. If it want much power, it has to go to other power producers for further power transactions.

	Real power	Reactive power
TC11	237.00 MW	104 50 Mvar
TC12	327.34 MW	140.29 Mvar
TC1	237 00 MW	104 50 Mvar
TC21	215.00 MW	92.50 Mvar
TC22	269.20 MW	115.37 Mvar
TC2	215 00 MW	92 50 Mvar
TTC	215 00 MW	92.50 Mvar
Base case transfer	210.00 MW	90.00 Mvar
ATC	5.00 MW	2.50 Mvar

Table 6.9 : Result summary

6.5 Comparison of results for different definitions of ATC

In chapter (3) some definition of ATC were discussed. These definitions were based on different system performance limits In this section results are compared on the basis of these definitions Table 6 10 shows the value of ATC calculated using different criteria as per the definitions.

Definition (5) is the standard definition as given by NERC [8]. According to it the criteria should be those limits which are responsible for reliable and secure operation of the system This definition indicates towards the ATC calculation in restrictive way which results in low

value of ATC Definition (4) mainly consider the voltage collapse limit for the ATC calculation This could be a restrictive limit in which reactive power support is not enough to satisfy the load demand For the Iceland 220kV system based on this the value of ATC comes to be 59 20 MW and 25 37 Mvar. Definition (2) consider only the line flow limits and voltage magnitude limits at the bus for both pre and post contingency conditions For the Iceland 220kV system this criteria is much more restrictive than voltage collapse criteria which gives ATC as 5 MW, 2 5 Mvar The values for definition (5) and (2) comes to be the same, since both the definitions consider line thermal limit as their criteria and for the Icelandic 220kV system it is the limiting condition for ATC

Definition	Criteria	TTC	ATC	Limiting condition
(2)	Line flow and bus voltage magnitude limits	215.0MW, 92 5Mvar	5 MW, 2.5 Mvar	line flow limit on line L9 for the contingency of line L4
(4)	Voltage collapse limits	269 20MW, 115.37Mvar	59.20MW, 25.37 Mvar	voltage collapse condition at bus 11 ISAL with the contingency of line L6
(5)	as applicable under individual system reliability operating criteria	215.0MW, 92 5 Mvar	5 MW, 2.5 Mvar	line flow limit on line L9 for the contingency of line L4.

Table 6.10 : Comparison of result using different definitions of ATC

The value of ATC depends on criteria considered for its calculation Results obtained from different definitions show the same. The definition given by NERC provides the most restrictive result for the system. The definition taken in this paper is the moulded form of the NERC definition Since the criteria taken in this paper are very restrictive thus it results in low value of ATC for the system

In this chapter the static ATC model was tested for the Icelandic system. The value of the ATC calculated for this system was 5MW, 2.5 Mvar This is a small value which implies that the transmission path between ISAL and Burfell is utilised nearly to its maximum capability The results obtained from the static ATC determination model were used to compare different definitions used in the literature. The comparison concluded that the value of ATC depends upon the criteria used for its calculation.

Chapter 7

Determination of ATC for the Indian UPSEB 400kV System

7.1 The UPSEB power system

The Indian UPSEB (Uttar Pradesh State Electricity Board) system exist in northern part of India. It has a total generation installed capacity of 6324 MW and total consumption of 6059 MW [22]. The principle resources of generation are coal and hydro energy. The major generating units are Singrauli, Rihand, Obra and Unchahar. Table 7.1 shows generating capacity and type of the major generating units of UPSEB system.

Generating Units	Installed capacity	Resource
Singrauli	1800	Coal
Anpara	570	Coal
Obra	900	Coal
Rihand	900	Coal
Unchahar	840	Coal
Dadri	817	Coal
Auraiya	454	Gas
Hajratganz B&C	515	Coal
Yamuna 1&4	355	Hydel

Table 7.1 : Main generating units in the UPSEB power system

Chapter 7

Determination of ATC for the Indian UPSEB 400kV System

7.1 The UPSEB power system

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Unchahar	840	Coal
Dadri	817	Coal
Auraiya	454	Gas
Hajratganz B&C	515	Coal
Yamuna 1&4	355	Hydel

Table 7.1 : Main generating units in the UPSEB power system

The main loads are the domestic and industrial loads at Kanpur, Agra and Lucknow Voltages used at the transmission level in UPSEB system are 400kV, 220kV, 132kV and at distribution level 33kV and 11kV The biggest generating station are at eastern part of Uttar Pradesh (UP) These main generating units also provide power to western part of UP Recently the north-west part of UP has been declared as a new state Uttranchal. It will be interesting to have the knowledge of maximum power that can be transfer through these main generating units at east to some cities of newly formed Uttranchal state The 400kV part of the UPSEB network is taken as the second study system for ATC calculation in this work

7.2 The UPSEB 400kV system

The study system taken here is the 400kV network of the UPSEB system A bulk amount of power is transferred at this transmission level. It is effective to calculate the ATC for a transmission path at this level since it provide a reasonable amount of ATC

Generating Unit	Generation capacity (MW)	Load centres	Consumption (MW)
Obra	900	Agra	470
Anpara	570	Kanpur	300
Singrauli	1800	NCR	-444
Auraiya	454	Rishikesh	100
Rihand	900	Rihand	1000
TOTAL	**4624**	*TOTAL*	**1426**

Table 7.2 : Generation and consumption in the UPSEB 400kV system

This system consist of 20 buses with 20 transmission lines and 5 transformers The main generating stations are Singrauli, Rihand, Obra, Anpara and Auraiya and the main load centres are Agra, Kanpur and Rihand (Table 7 2). Obra is one of the largest generating unit in the system with a installed generating capacity of 900 MW, 400 Mvar. This is taken as slack bus for the system. The transmission path is selected between the biggest generating station at Singrauli (lie at east part of UP) and the load centre at Rishikesh (a city in newly formed Uttranchal state) for the calculation of ATC to have the knowledge about extra power which can be transferred from UP to Uttranchal through this path.

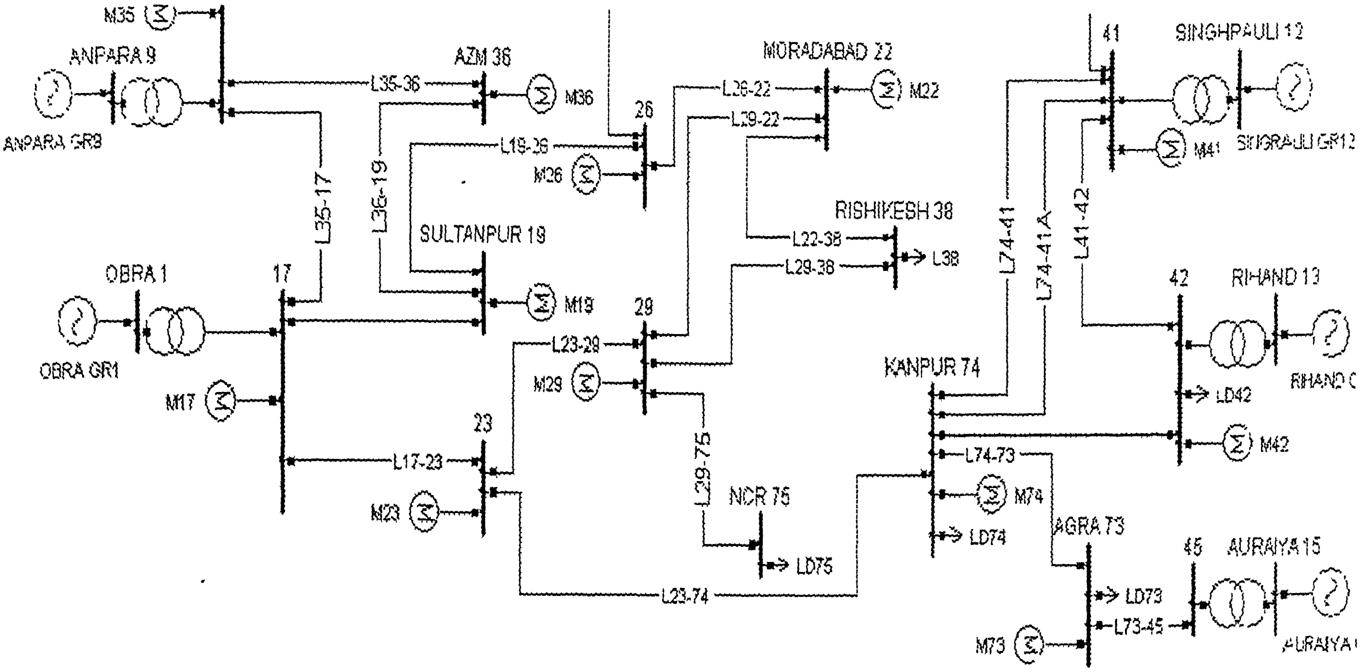


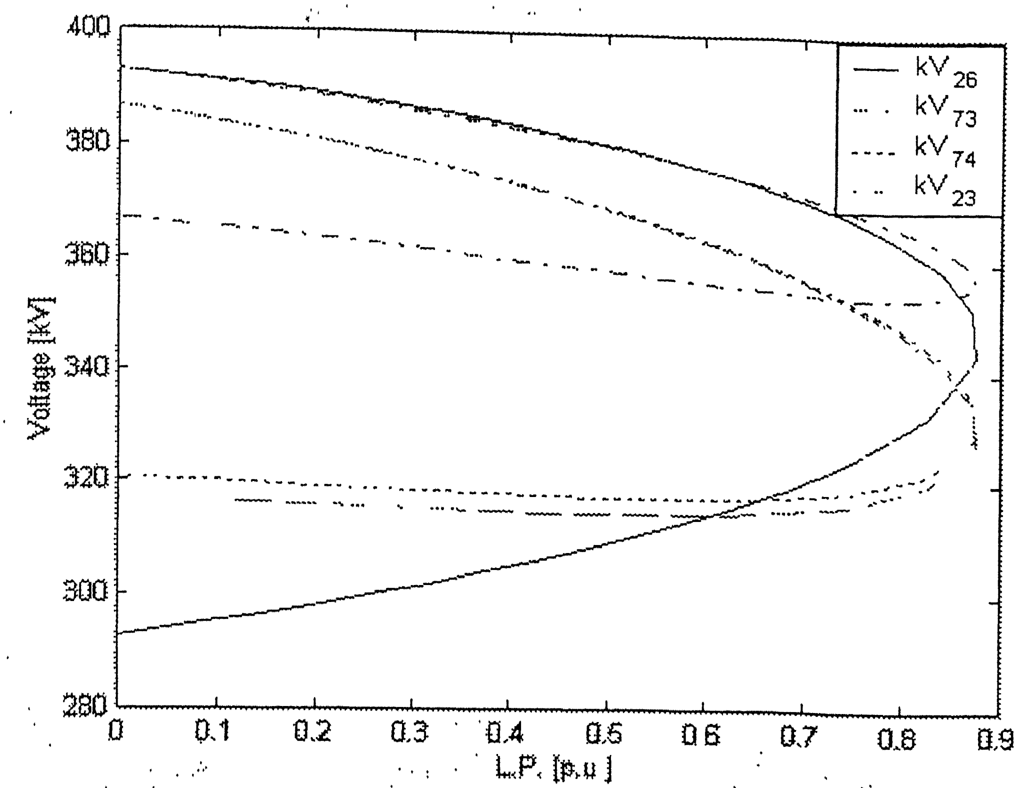
Figure 7 1 : Indian UPSEB 400kV system

7.3 The base case

The value of the ATC depends upon the base case condition of the system above which the ATC is to be calculated. At the selected base case condition all the ATC criteria should be satisfied. The system considered here is a part of UPSEB grid in which only 400kV buses and transmission line are considered (Figure 7.1). Due to this, some adjustment are done to get a required base case condition. The main generating units at Rihand, Singrauli and Auraiya also deliver power to 200kV network and other neighbouring states Thus the output generation of these units are reduced from actual values for the reliable base case condition. Some small loads are also neglected The generation and load condition for selected base case are given in Table 7.3.

Generating Unit	**Generation (MW)**	**Load centres**	**Consumption (MW)**
Obra	108	**Agra**	470
Anpara	150	**Kanpur**	300
Singrauli	700	**Rishikesh**	100
Auraiya	150	**Rihand**	1000
Rihand	350	**NCR**	-444
TOTAL	**1458**	***TOTAL***	**1426**

Table 7 3 . Generation and consumption in the UPSEB 400kV system for the selected base case condition



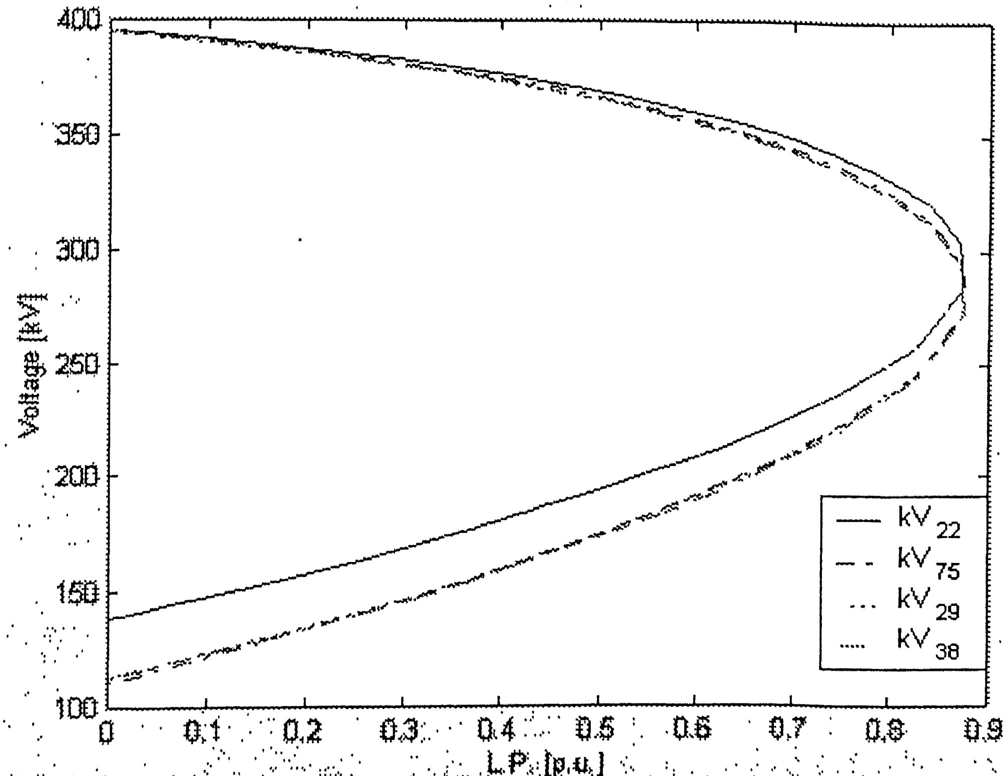


Figure 7.2 : P-V curve at load buses at base case condition

For the selected base case condition the limiting values for line loading and bus voltage magnitude are given in Table 7 4 and voltage collapse profiles for different buses are shown in Figure 7.2

The maximum line loading occurs at line L74-73 which is the 91 6% of its thermal limit. The minimum voltage occurs at bus 29 which is 361kV. It is within the bus voltage limit which is taken 80% - 120% of the rated bus voltage (400kV). The voltage profile shows that the system is far from the voltage collapse point The base case condition corresponds to zero value of load parameter and voltage collapse point at 0.887 p.u value of load parameter The base value for load parameter is taken as 100MVA.

Hence the selected base case satisfy the ATC criteria. Now further amount of available power that can be transfer through the selected transmission path between Singrauli and Rishikesh is to be calculated for this system condition.

Limiting condition	Limiting value
Maximum line loading	At line L74-73, 91.6 % of thermal limit
Minimum Bus voltage magnitude	At bus 29, 361 kV

Table 7.4 : Limiting values for the base case condition

7.4 Calculation of ATC

The static ATC determination model developed in section 5.4 is used to calculate the ATC for selected base case condition and transmission path for UPSEB 400kV system

7.4.1 The TC1 determination

Starting from the base case condition, the load at load centre Rishikesh (bus 38) is increased in incremental steps with the corresponding increase in generation at Singrauli. Both real and reactive power is varied assuming constant power factor at bus 38 At the loading condition of 275MW and 82.5Mvar at bus 38, limiting condition is reached since the minimum voltage limit is hit at bus 38. This gives TC11 Table 7 5 shows the calculated TC11

	P	Q	Limiting condition
TC11	275MW	82.5 Mvar	Voltage at bus 38 hit lower limit i e 321kV (80.26 %)

Table 7 5 : TC11 determination

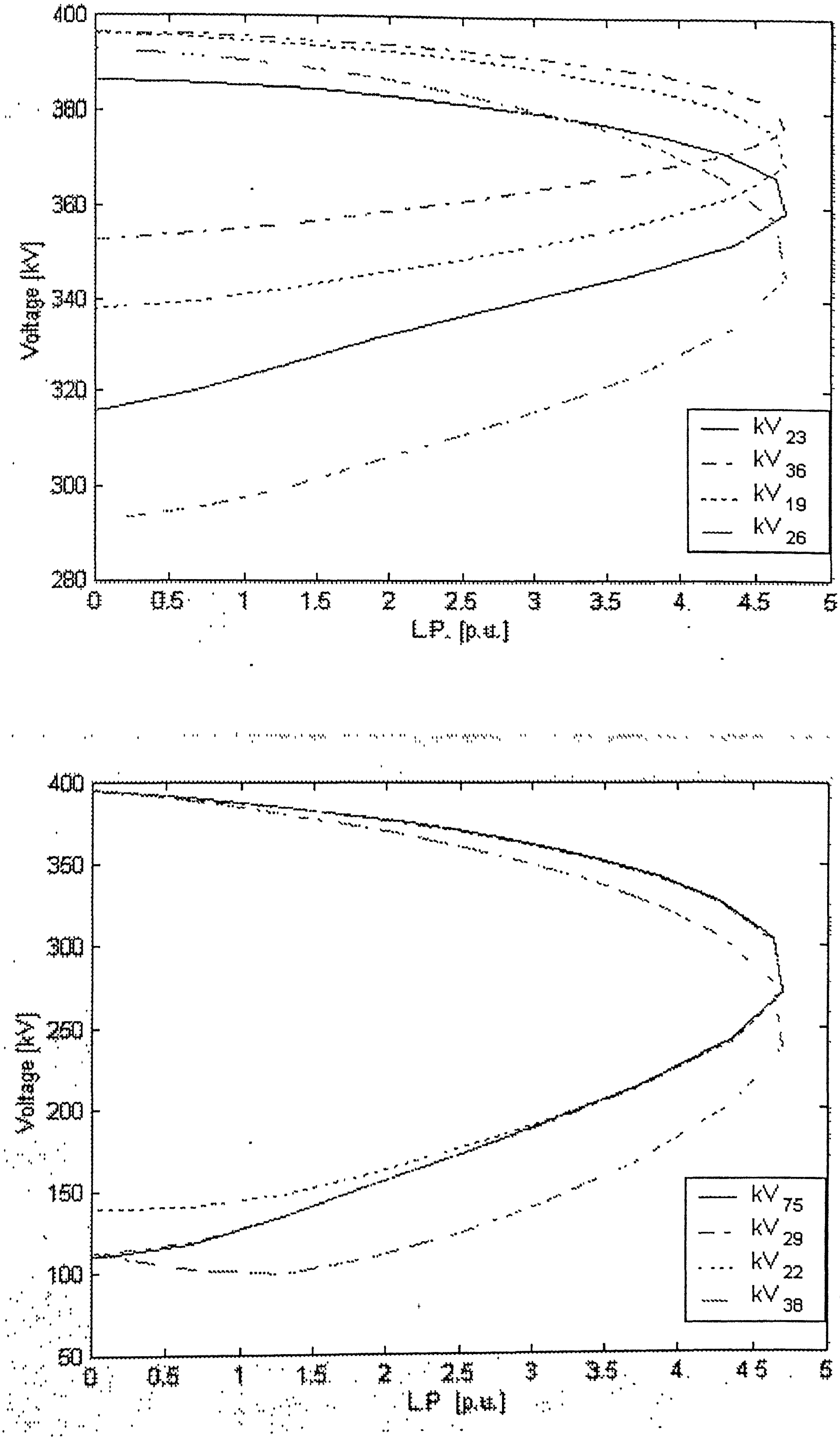


Figure 7 3 · P-V curve at load buses with varying power transfer on selected transaction path

For the calculation of TC12 , continuation power flow method is used to find the maximum load-parameter (λ_{max}) at saddle node bifurcation point starting from the base case condition Figure 7 3 shows the voltage profile at different buses The variation of load and generation is considered only at bus 38 and Singrauli respectively Table 7.6 shows the result for TC12

	P	Q	λ_{max}	Critical bus	$V_{critical\ bus}$
TC12	569.61 MW	170.83 Mvar	4.6961	38	237.52 kV

Table 7.6 . TC12 determination

The maximum load-parameter found was 4 69610. At this point the minimum voltage occurs at bus 38 i.e 237.52kV Thus TC12 is the loading condition corresponding to maximum load-parameter which comes to be 569.61 MW and 170.83 Mvar

Hence, the transfer capability of the system with all elements present in the system is given as.

TC1 = Minimum { TC11, TC12 } = 275.0 MW and 82.5

7.4.2 The TC2 determination

Line outage contingencies are considered for the determination of TC2 since these are frequent as compared to generator outages. Outage of lines L29-38, L22-38, L74-41, L74-42, L35-17, L17-19, L36-19 and L35-36 are taken. For each line outage condition, with incremental load and generation increase at Rishikesh and Singruali respectively, the transfer capability is calculated (Table 7.7)

Contingency	Transfer Capability		Limiting condition
	P (MW)	Q (Mvar)	
L29-38	140	42.0	Minimum voltage limit at bus 38
L22-38	155	46.5	Minimum voltage limit at bus 38
L74-41	143	42.0	Max line thermal limit hit at line L74-73
L74-42	125	37.5	1. voltage limit at bus 29 2. thermal line limit at line L74-73 3. thermal limit at line L29-75
L35-17	270	81.0	Min voltage limit at bus 38
L17-19	215	64.5	Min voltage limit at bus 38
L36-19	255	76.5	Min voltage limit at bus 38
L35-36	245	73.5	Min voltage limit at bus 38

Table 7.7 : Transfer capability for contingency condition considering thermal and voltage limits

Thus TC21 which is minimum of the transfer capability for different line outages comes out to be 125 MW and 37 5 Mvar for the outage of line L74-42.

For the determination of TC22, transfer capabilities are calculated for different line outages taking voltage collapse criteria Continuation power flow is used for different line outages Table 7 8 shows the maximum load-parameter and the corresponding transfer capability for different line outages conditions. Bus 38 (Rishikesh) is seen to be the critical bus in every contingency condition since the load is increased at only this bus during continuation power flow without providing any extra reactive power support Voltage corresponding to voltage instability point at the critical bus is also shown in Table 7.8.

Contingency	λ_{max} (p.u.)	Transfer capability		$V_{critical\ bus}$ (kV)
		P (MW)	Q(Mvar)	
L29-38	2.7617	376.17	112.85	221 58 kV
L22-38	2.8325	383.25	114.97	216.36 kV
L74-41	4.4693	546.93	164.07	253 46 kV
L74-42	4.8451	584.51	175 35	254 35 kV
L35-17	4.6562	565 62	169.68	235.00 kV
L17-19	4 4924	549.24	164.77	255 36 kV
L36-19	4.5831	558.31	167.49	266.00 kV
L35-36	4.5653	556.53	166.95	261 88 kV

Table 7.8 · Transfer capability for contingency condition considering voltage collapse limit

Thus TC22 which is minimum of transfer capability for different line outages considering voltage collapse criteria comes out to be 376.17 MW and 112.85 Mvar. This is the transfer capability corresponding to outage of line L29-38. Figure 7.4 shows voltage profile of different buses for this condition.

Hence TC2 is calculated as,

$$\boxed{TC2 = \text{Minimum}\ \{ TC21, TC22 \} = 125.0\ \text{MW},\ 37.5\ \text{Mvar}}$$

This is the transfer capability of the system considering contingency conditions.

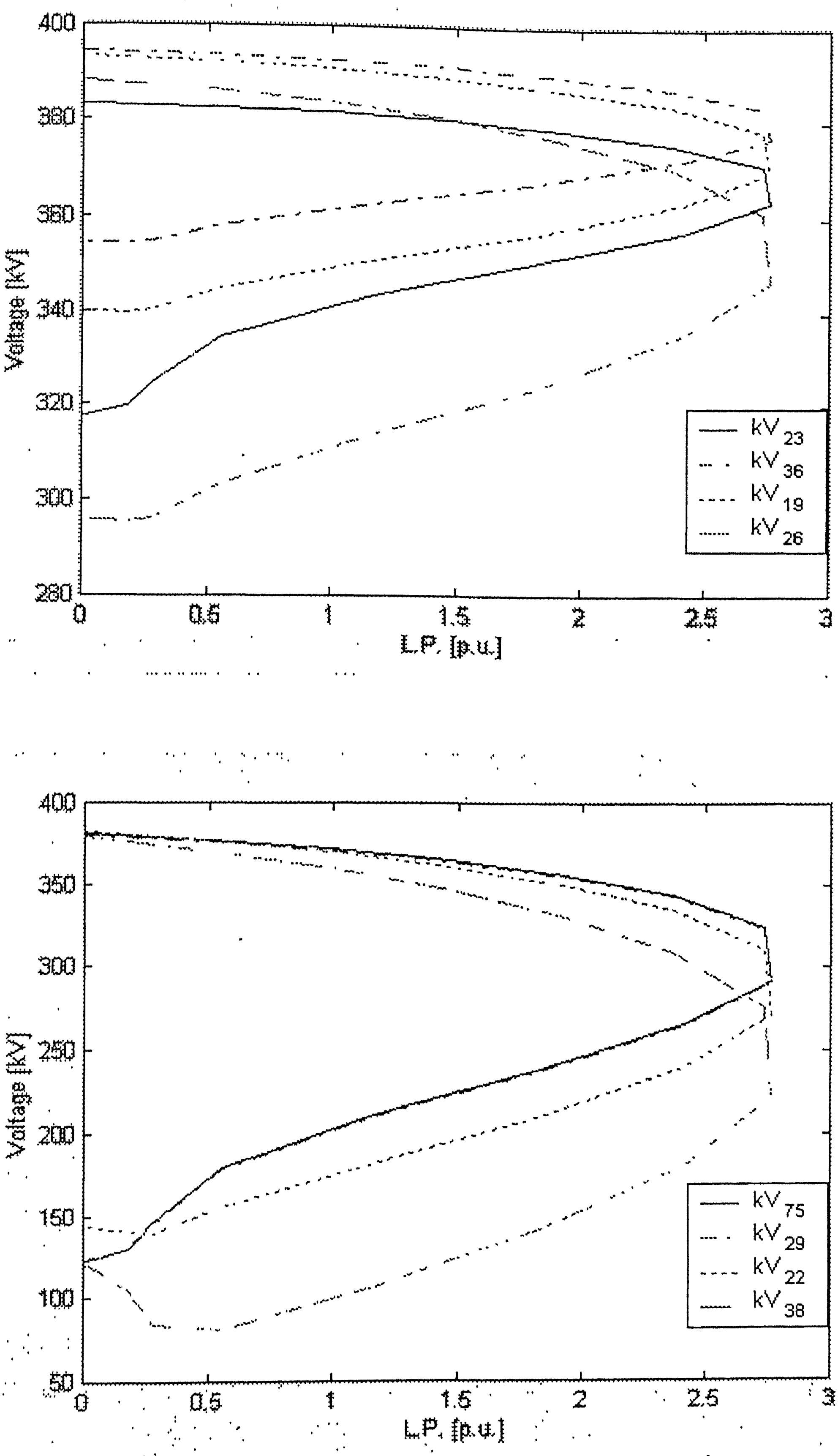


Figure 7 4 · P-V curve at load buses for the critical contingency (L29-38)

7.4.3 The TTC determination

The total transfer capability of the system considering line thermal limit, bus voltage magnitude limit and voltage collapse criteria for both pre and post contingency criteria is given as

$$\boxed{TTC = \text{Minimum}\{TC1, TC2\} = 125.0MW \text{ and } 37.5Mvar}$$

7.4.4 The ATC determination

The ATC for the transaction path between Singrauli and Rishikash in UPSEB 220kV system is calculated as .

ATC = TTC – Base case transfer for Singrauli- Rishikesh transaction path = 25 MW, 7.5Mvar

$$\boxed{ATC = 25.0 \text{ MW and } 7.5 \text{ Mvar}}$$

Table 7.9 shows the summary of results. The ATC calculated comes out to be 25 MW, 7.5 Mvar which indicate a reasonable value of power that can be still transfer from Singrauli to Rishikesh without violating the system security limits.

	Real power	Reactive power
TC11	275.00 MW	82 50 Mvar
TC12	569.61 MW	170.83 Mvar
TC1	275.00 MW	82.50 Mvar
TC21	125.00 MW	37 50 Mvar
TC22	376.17 MW	112.85 Mvar
TC2	125 00 MW	37.50 Mvar
TTC	125.00 MW	37 50 Mvar
Base case transfer	100.00 MW	30 00 Mvar
ATC	25 00 MW	7.50 Mvar

Table 7.9 · Result summary

In this chapter the static ATC determination model was tested for the UPSEB 400kV system The result obtained using this model is satisfactory. The ATC calculated for the transmission path between Singrauli and Rishikesh came to be 25MW, 7 50 Mvar. This implies that this transmission path can be used for further transaction of power from the main generating unit of UP to the domestic loads of cities near Rishikesh

Chapter 8

Determination of Dynamic ATC for Single Machine Infinite Bus System

8.1 Single machine infinite bus (SMIB) system

The method developed for the determination of dynamic ATC in this work is tested on a single machine infinite bus system. This simple system is helpful to understand the basic effects and the concepts involved in the methodology used in this work. This also provides a clear view of calculating dynamic ATC by giving step by step calculation By having an appropriate knowledge for the physical aspects of the phenomena and gain experience with the analytical techniques, using this small system, the process could be extended for large complex system. The SMIB system consists of a synchronous generator connected to a very large system through a transmission line. The large system is represented by an infinite bus The infinite bus acts as voltage source of constant voltage and constant frequency. For a given system condition, the magnitude of the infinite bus voltage remains constant when the machine is perturbed. With the change in steady state system condition the magnitude of the infinite bus voltage changes to represent the change in operating condition in the external network The synchronous generator in the system is represented by its classical model that is by its internal voltage behind the direct axis reactance The resistance are neglected. The internal voltage of the machine is assumed to be constant for pre and post contingency condition and the load change conditions Figure 8 1 shows the SMIB system configuration.

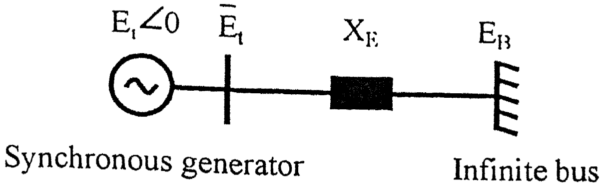


Figure 8 1 · SMIB system

8.2 Determination of dynamic ATC considering steady state stability criteria

8.2.1 Initial condition

At initial condition for the SMIB system the values [19] are given as ·

Base MVA = 2220 MVA

Base voltage = 24 kV

Real power output of generator P = 0.9 p.u.

Reactive power output of generator Q = 0.3 p.u

Terminal voltage $E_t = 1.0\angle 0$

Direct axis reactance $X_d = 0.3$

Inertia constant H = 3 5 MW sec/MVA

Damping coefficient $K_D = 10.0$

Thus, for initial condition from equations 5.24, 5.25 and 5.26, one gets :

generator internal voltage $E_i = 1.123\angle 13.94°$

infinite bus voltage $E_B = 0\ 995\angle\text{-}36°$ and

load angle $\delta_o = 49.94°$

8.2.2 Determination of steady state stability limit

Starting with this initial condition, the power transfer from the generator to the infinite bus is increased with an increment of 0.001 p.u i.e 2.22 MW till the load angle δ reaches 90°. Both the real and reactive power transfer are increased with a constant power factor.

Different power transfer cases are considered to have a clear picture of the maximum power transfer limit associated with steady state stability. The power transfer condition at which the

load angle reaches the value of 90° is considered to be the steady state stability limit It is also interesting to see power transfer condition for two other criteria for steady state stability limit These are

1 When the real part of eigen value of characteristic equation (5 38) are approaching zero
2. When change in δ due to change in power transfer have a increasing slope and it is not settling to some steady state value.

It is interesting to see the behaviour of the system for different power transfer cases Calculated value of different parameters for different cases are shown in Table 8.1 and the time response of load and rotor angular frequency are shown in Figure 8 2 - 8 6 These calculations have been done by using the methodology discussed in section 5 2.1.

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5
Real power transfer (pu)	0.9	1.45	1.8944	1.89592	1.9
Reactive power transfer (pu)	0.3	0.483	0.63146	0.63197	0.633
Load angle (deg)	49.944	74.7979	90.0003	90.0457	90.1674
Damping torque coefficient (pu torque/pu speed)	10	10	10	10	10
Synchronising torque coefficient (pu torque/rad)	0.7574	0.3950	0.0015	2.8316 × 10^[illegible]	-0.0040
Eigen values	-0.7143 + 5.7847i	-0.7143 + 4.1485	-1.3798	-1.4286	-1.5457
	-0.7143 - 5 7847i	-0.7143 + 4.1485	-0.0487	0.0001	0.1171
Undamped natural frequency (rad/sec)	5.8287	4.2096	0.2593	0.0091i	0.4254i
Damping ratio	0.1225	0.1697	2.7548	-78.8019i	-1.6789i
Damped frequency (rad/sec)	5.7847	4.1485	0.6656i	0.7143i	0.8314i

Table 8.1 · Parameter values for different power transfer cases

Case 1

This case corresponds to the power transfer condition of 0.9 p u. real and 0.3 p.u reactive With the application of this load the rotor angle and the rotor angular frequency oscillates The time response of the rotor angle and angular frequency is shown in Figure 8.2. The value of synchronising torque coefficient and damping torque coefficient is given in Table 8 1

Since these are enough to damp out the rotor oscillation thus after some time interval the rotor angle settles to a value of 49.94° which is less than 90° and also during oscillation it does not crosses this limit The eigen values calculated (Table 8.1) are also having negative real part Thus system is stable considering steady state stability

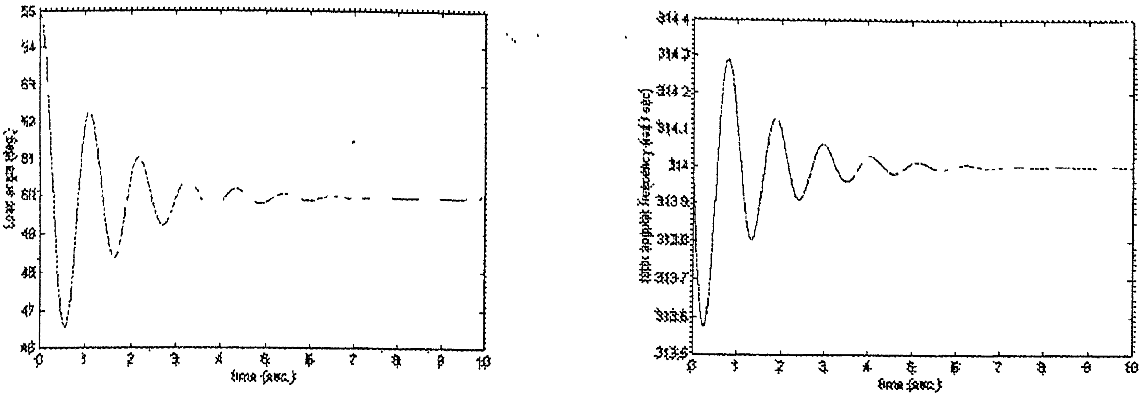


Figure 8 2 · Time response of load angle and rotor angular frequency for Case 1

Case 2

This case corresponds to power transfer condition of 1.45 p.u. real, 0.483 p.u. reactive. At this loading condition the rotor oscillates with higher amplitude (Figure 8.3) compared to Case 1 and it settles down at much higher value i.e. 74 797° In this also the rotor angle does not cross the 90° limit and the eigen values are having negative real part (Table 8 1) This also corresponds to a stable condition but at some higher value of rotor angle

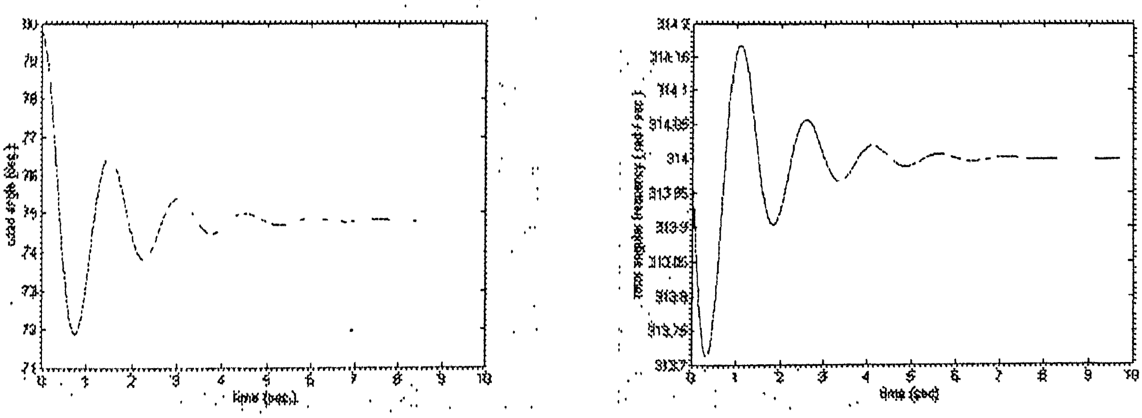


Figure 8.3 . Time response of load angle and rotor angular frequency for Case 2

Case 3

This case corresponds to power transfer condition of 1 8944 p.u real , 0 63146 p u reactive At this condition the rotor angle crosses the 90° limit. The time response shows that the behaviour of rotor angle is not oscillatory. Rotor angle shoots up to a maximum value and then starts decreasing (Figure 8.4). But it is settling with very slow rate. The eigen values are having negative real part (Table 8 1) that means this criteria is not violating. It is a unstable case since the rotor angle crosses the limit of 90°. But it is also interesting to check at which power transfer condition the other two criteria are violating For this case 4 and 5 are considered

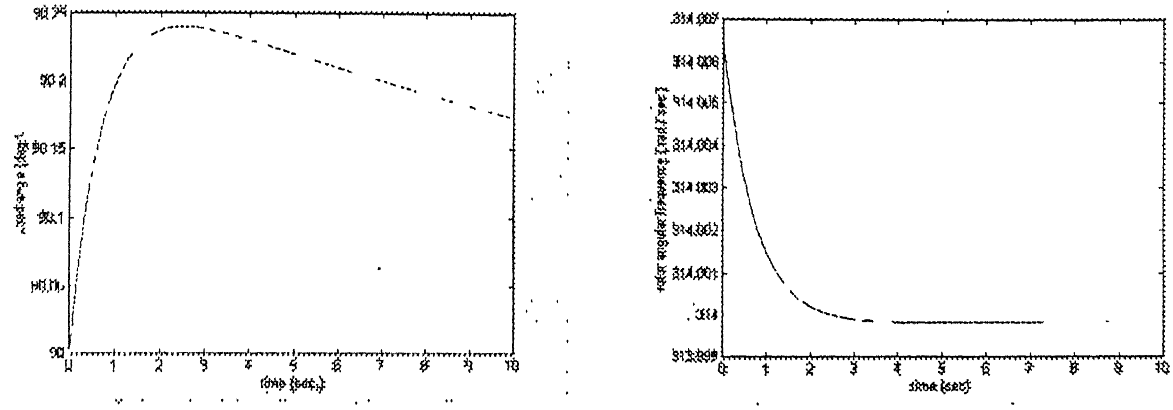


Figure 8 4 : Time response of load angle and rotor angular frequency for Case 3

Case 4

This case corresponds to power transfer condition of 1 89592 p.u real, 0.63197 p.u reactive. The rotor angle is going beyond the 90°. One of the eigen value has become positive (Table 8 1) In this case rotor angle shoots up to a maximum value which is greater then 90° and remain constant at this value (Figure 8.5).

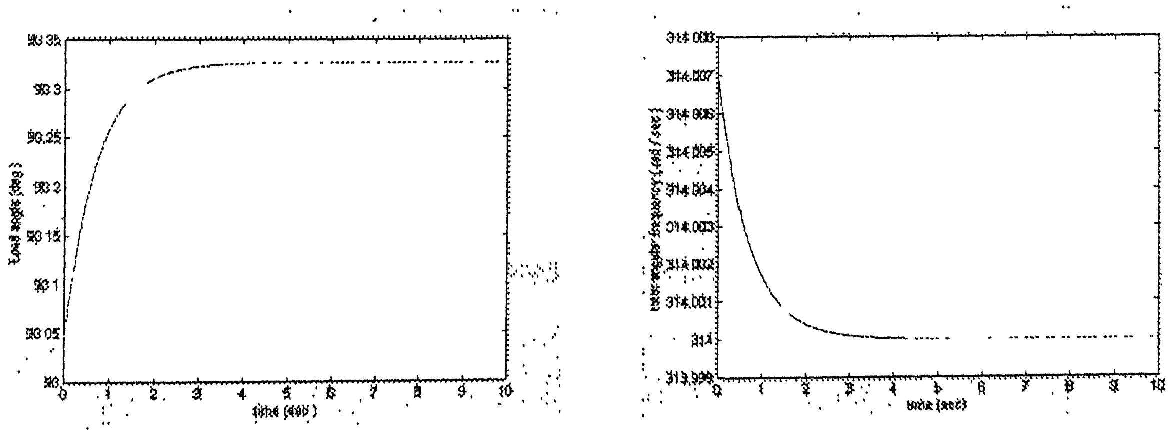


Figure 8 5 : Time response of load angle and rotor angular frequency for Case 4

Case 5

This case corresponds to power transfer condition of 1 9 p.u. real, 0.633 p u. reactive In this case also the rotor angle goes beyond the 90° and one of the eigen values becomes more positive (Table 8 1). The time response of the rotor angle is having a continuous increasing slope which leads to loss of synchronism of the generator

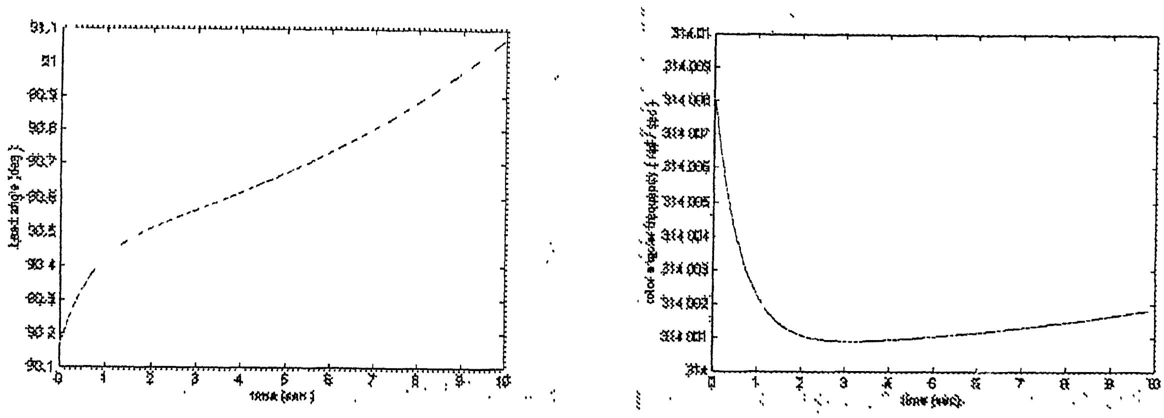


Figure 8.6 : Time response of load angle and rotor angular frequency for Case 5

At the power transfer condition of Case 3 the rotor angle crosses the limit of 90° which is considered to be the primary criteria for steady state stability of the system. Thus the total transfer capability of the SMIB system due to steady state stability is 1 8944 p u real, 0.63146 p u. reactive Thus ATC is given as,

ATC = TTC – initial power transfer by the generator

= (1.8944, 0.63146) – (0.9, 0.3)

= 0.9944p.u real, 0 33146 p.u. reactive

Thus for this small system, if the generator has the capacity it can still export approximately double of its initial power transfer.

For steady state stability limit calculation in a muti-machine system this dynamic ATC determination model has to be extended. The analysis of multi-machine system also requires the representation of interconnecting transmission network, static and dynamic loads and other devices like SVC etc. Due to this, the number of algebraic and differential equations will increase. A common reference frame is used for measuring the machine rotor angle. Axes transformation equations are used to transform between the individual machine d-q reference frames and common reference frame [19]. The equations are linearised around an operating

point in which all other elements other than state variables are eliminated These linearised state equations can be used for load angle calculation of machines for different power transfer condition The transfer capability of the system will be the limiting power transfer at which the load angle of any machine crosses an appropriate value with respect to common reference frame

In this chapter, dynamic ATC determination model was tested for the SMIB system load angle limitation is considered to be the primary criteria for steady state stability limit analysis Power transfer cases at which other two criteria i.e eigen value criteria and time domain criteria violates were also discussed Transient stability limit can also be considered for dynamic ATC calculation.

Chapter 9

Conclusions

To have open access and non-discriminatory operation in a deregulated market, a transparent knowledge of the system capability is beneficial. This paves the way for the determination of ATC in a deregulated power system. The ATC value serves as an important indicator of system performance. It is useful in making power transaction contracts in the system

This work made an attempt to provide a deterministic based approach for the calculation of ATC The models for the ATC determination were developed based on the static as well as the dynamic criteria Under the static criteria line thermal limit, bus voltage limit, generator real and reactive power limit and voltage stability limits were considered The Newton Raphson method and the continuation power flow method were used as tools for static ATC calculation. The developed model for static ATC determination was tested on two practical systems, the Icelandic 220kV system and the Indian UPSEB 400kV system. Under the dynamic criterion, only steady state stability limit was considered. Load angle calculation, eigen value analysis and time domain analysis were used for steady state stability limit calculation. The model for dynamic ATC determination was tested for single machine infinite bus (SMIB) system.

From the test results it can be concluded that the value of ATC depends upon the criteria considered for its determination. The limiting condition for ATC calculation also depends upon the system operating conditions. The ATC determination models provide a reasonable and dependable value of ATC of the transmission path for the study systems.

These models provide a clear step by step procedure for ATC determination The transfer capability is calculated for each of the static and dynamic criteria limit. These models also indicate the limiting conditions which restricts the value of ATC in the system These models can be used for off-line ATC determination for a particular snapshot of the system condition The steps defined in these models can be used as an algorithm for the development of software for on-line ATC calculation With the knowledge of the limiting condition, the system operator can take some operating or planning decisions for enhancing the ATC value

The following aspects are being identified for further research in the area of ATC determination

- The idea of introducing transient stability criteria is also given in this work but not tested This should also be considered for ATC determination to have much reliable value
- The model for dynamic ATC determination is tested only for SMIB system in this work and it can be extended for the analysis of multi-machine system.

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